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ANALYZING THE EFFECT OF FIXED AND MOVING BOTTLENECKS ON TRAFFIC FLOW AND CAR ACCIDENTS IN A TWO-LANE CELLULAR AUTOMATON MODEL

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Traffic bottleneck is considered as one of the major causes of the disturbance in traffic flow. The understanding the dynamics between vehicles and bottlenecks is crucial for enhancing traffic flow and ensuring road safety. This research examines a two-lane traffic cellular automaton model to understand the effects of static (e.g., lane reductions) and dynamic (e.g., slow-moving vehicles) bottlenecks on traffic flow and road safety. We found that at low vehicle densities, slow vehicles gravitate towards the open lane, while faster vehicles switch lanes to overtake, returning to their original lane post-bottleneck. At high densities, traffic flow near static bottlenecks ceases, independent of bottleneck length. Safety analysis shows that extended static bottlenecks reduce rear-end collision risk due to fewer lane changes and increased vehicle stationarity. At maximum density, gridlock nullifies the chance of such collisions. Our findings provide actionable insights for traffic planning focused on bottleneck management to improve road safety.

Keywords: fixed bottleneck, fundamental diagram, rear-end collision, lane-changing collision, two-lane

1 INTRODUCTION

In our rapidly urbanizing world, traffic congestion has emerged as a major challenge affecting many countries. This widespread issue not only puts enormous economic and social pressure on individuals and communities, but also threatens the environmental sustainability and quality of life in urban centers. Traffic congestion attracted the attention of scientists from different backgrounds [1-8]. What is at the heart of this problem is traffic 'jamming', which occurs when the number of vehicles exceeds road capacity, can arise due to various factors such as bottlenecks. A bottleneck basically refers to the narrowest point of traffic flow, which occurs when upstream vehicle density overshadows downstream density. We can categorize bottlenecks into two main types: dynamic and static. A particular example of a static bottleneck is a fixed bottleneck, which refers to a non-mobile obstruction, such as roadwork or a lane closure, that reduces the available road space and disrupts the normal traffic flow. A specific instance of a dynamic bottleneck is a moving bottleneck, which refers to a slow-moving vehicle, such as a bus, that travels at a speed much lower than the surrounding traffic flow [9]. Scholars across multiple fields have dedicated efforts to thoroughly examine the dynamics of both dynamic and static bottlenecks, aiming to comprehend their distinct impacts on traffic patterns [9-23]. Daganzo and Laval [18] introduce a numerical approach for simulating kinematic wave traffic streams, specifically accounting for slow vehicles by treating them as moving boundaries within the flow. Their model effectively converges in terms of flow, density, and speed, offering oscillation-free predictions, making it suitable for analyzing the impact of traffic streams on bottlenecks. Wang et al. [19] explored the dynamics of deterministic capacity drops at traffic bottlenecks, revealing their substantial influence on commuters' departure times, traffic flow evolution, and congestion patterns during the morning commute in corridors with tandem bottlenecks, offering novel insights into trip costs, the capacity expansion paradox, and strategic traffic management. Yu et al. [20] addressed the challenge of lighting-induced traffic bottlenecks in long freeway tunnels during the daytime by proposing an intelligent driver model with location-dependent lighting-related desired speed (IDM-LLDS), which captures the complex interactions between variable tunnel lighting, drivers' visual adaptation, and consequent car-following behavior, suggesting adaptive lighting strategies and portal sunscreens as mitigative measures for these unique bottleneck conditions. Chen et al. [21] devised variable speed limit (VSL) strategies based on Kinematic Wave theory, tested through simulation to alleviate congestion, and optimize flow at freeway bottlenecks due to non-recurrent events, and showcased through analytical formulations the potential delay reductions achievable with these strategies. Juran et al. [22] focused on the disruption caused by moving bottlenecks, such as heavy-load trucks or oversized vehicles, on highway traffic flow and network performance. Recognizing the limitations of existing transportation tools to evaluate the impacts of such bottlenecks over long distances, they developed a dynamic traffic assignment (DTA) model. This model was designed to assess the effects of moving bottlenecks on travel times and routes within a network, accounting for the specific characteristics of the bottleneck. By utilizing a mesoscopic simulation that adhered to traffic dynamics principles, the model could account for variations in traffic density and speed, effectively capturing the queues that formed behind moving bottlenecks. Fang et al. [23] extend the full velocity difference model [24] to analyze traffic flow and moving bottlenecks on two-lane highways. They explore vehicle movements, bottleneck dynamics, and lane-changing behaviors, providing insights through numerical simulations. Zheng et al. [25] conducted empirical and experimental studies on the US-101 and German-A5 freeways to understand how traffic oscillations develop along roads with fixed bottlenecks, finding a concave growth pattern that was also evident in traffic platoons behind moving bottlenecks. Their work, which includes tests against car-following models, reveals inadequacies in the intelligent driver model (IDM) [26] while highlighting the accuracy of the 2D-IDM and stochastic speed adaptation model in capturing this behavior. Ou and Tang [27] proposed an extended macro traffic flow with a moving bottleneck model to study the effects of a moving bottleneck on the evolution and propagation of traffic flow under uniform flow and a small perturbation. Hanaura et al [28] derived the fundamental diagrams of a two-lane highway with a few slowdown sections. Significantly, they elucidated the relationship between traffic density and jam lengths, employing both analytical methods and traffic simulations to provide a detailed exploration of this dependency.

In the realm of traffic simulation, Cellular Automaton (CA) models have been instrumental in shedding light on various aspects of vehicular dynamics. These models, as explored in prior research, primarily focus on differentiating vehicle speeds, implementing diverse lane-changing rules, and capturing a range of driver behaviors.

Hence traffic bottlenecks either moving or static have been extensively studied using various CA models, each contributing unique insights into traffic behavior. For instance, Chowdhury et al. [29] expand upon the Nagel and Schreckenberg (NaSch) model [30] to create two-lane traffic simulations incorporating vehicles with two distinct maximum speeds. They present two models: a symmetric version that treats lanes and vehicle types equally, and an asymmetric version with unique lane-changing rules and anticipatory driving behaviors for faster vehicles to prevent being caught behind slower ones. They found that the higher contribution of the fast vehicles to the throughput is observed when the asymmetric lane-changing rules model is adopted (here the asymmetric lane changing rules refers to the case when the fast vehicles have priority over the slow one in a lane, the slow ones must shift to the slow lane). Knospe et al. [31] expand upon the NaSch model [30] and explored the influence of slow cars on platoon formation in two-lane traffic models, a phenomenon well-established in single-lane scenarios at low densities. Their findings reveal that even a few slow vehicles can lead to platoon formation at low densities. They examine the persistence of this effect across various lane-changing rules and single-lane dynamics, noting that driver anticipation significantly mitigates the impact of slow cars. Lakouari et al [32] studied the interactions between vehicles in bidirectional traffic CA model with two types of vehicles (slow, fast). They found that when the density of one lane increases the slow-moving vehicles control the other lane by imposing their speed over the fast vehicles. Zeng et al [33] proposed a CA model to simulate the traffic flow characteristics under the combined bottleneck of accidents and on-ramp. They observed that the congestion caused by the accident will propagate upstream under the saturated flow. Chau et al [34] investigated the effect of tollbooths on the traffic flow in a single lane CA model based on Fukui and Ishibashi Fukui and Ishibashi [35] as well as the green wave model proposed by Torok and Kertesz [36]. Furthermore, On-ramps and off-ramps have been studied using CA models in Refs [37-41]. As the bottleneck can provoke jams in real traffic it can also induce accidents. Marzoug et al [42] applied the NaSch model [30] to analyze the probability of car accidents at a junction where two lanes merge. They found that non-cooperative driving significantly increases the risk of accidents, especially at medium to high traffic densities. The research also explores how speed limits at the bottleneck influence safety, concluding that higher speed limits may increase accident risk in low-density situations but improve safety in high-density conditions. However, the model does not account for overtaking or lane-changing and assumes a uniform vehicle type, overlooking the diversity of real-world traffic.

In this paper, we introduce a two-lane CA model that considers both moving and static bottlenecks. We've gone a step further in this traditional modeling approach by embedding elements of static (like work zones or lane reductions) and dynamic (such as slow-moving vehicles) bottlenecks. This enhancement significantly broadens the scope of the model, enabling it to better inform traffic planning and safety analysis in practical settings. Here, the initial configuration of our model does not distinguish between lanes as 'fast' or 'slow,' but rather positions both types of vehicles i.e., slow, and fast in both lanes with equal probability. This homogenous distribution allows us to understand more how a fixed bottleneck, located in one lane, influences lane-changing behaviors and overall traffic dynamics. Hence, in this study we explore the relationship between the length of the bottleneck and various traffic properties, such as the profile of stopped vehicles and the frequency of their speeds. We also delve into how these bottlenecks affect the probability of vehicle collisions, adding another layer of complexity to our analysis. While our focus is on CA models, it's noteworthy that alternative simulation methods, such as fluid-dynamic models or agent-based simulations, also hold potential for exploring traffic dynamics. These methods provide different perspectives and could uncover additional factors influencing traffic flow and safety. Opting for a CA model in our study was a strategic choice, driven by its adeptness in modeling intricate traffic behaviors while maintaining simplicity and computational efficiency.

The rest of the paper is organized as follows, in section 2 we will present the methodology of this investigation, hence for the section 3 we will discuss the results, the conclusion is given in section 4.

2 METHODOLOGY

The two-lane CA model mimics two adjacent unidirectional roads, here each lane in the model is composed of L cells. Each cell can be either empty or occupied by only one vehicle. The accumulation in our model is forbidden, it means that it is not allowed that one cell can be occupied by two vehicles. The vehicles are characterized by their speed (v_i) and position (x_i). The vehicles differ according to their maximum allowed speed, where the maximum speed of the slow (fast) vehicles is v_{max}^{s} (v_{max}^{f}).

The vehicles are uniformly distributed all over the two lanes according to the fraction of fast (f_f) and slow vehicles (fs). The longitudinal motion of vehicles is described by the Nagel and Schreckenberg model (NaSch) according to the following rules.

2.1 Longitudinal motion

R_1: Speed adaptation: $v_i \rightarrow Min\ (v_i + 1, v_{max}^{f\ or\ s})$.

R_2: Safety braking: $v_i \rightarrow Min\ (v_i,\ d_i)$.

R_3: Disturbance: $v_i \rightarrow Max\ (v_i - 1, 0)$. With probability *p*.

R_4: Motion: $x_{i+1} \rightarrow x_i + v_i$.

d_i denote the number of free cells in front of the vehicle *i*, where $d_i = x_{i+1} - x_i - 1$.

2.2 Lateral motion

The interaction between the two lanes is introduced by the lane-changing rules. The movement of vehicles is divided into two sub-steps. In the first sub-step: vehicles change lanes in parallel according to lane-changing criteria. In the second sub-step: both lanes are treated as a separate single lane where the NaSch model is applied [30]. We considered the model proposed by Rickert et al [43]. where the rules of lane-changing consider two criteria.

- Incentive criterion

R_1': $d_i(t) < v_d = Min\left(v_i + 1, v_{max}^{(f\ or\ s)}\right)$.

- Safety criteria:

R_2': $d_o(t) > d_i(t)$.

R_3': $d_b(t) \geq v_{max}^{(f\ or\ s)}$.

Here, $d_b(t)$ ($d_o(t)$) denote number of free cells behind (in front) of the vehicle *i* in the other lane (see Fig.1), while v_d is the desired speed of the vehicle *i* at instant *t*.

Even all those criteria are met the lane-changing is probabilistic process, therefore the vehicles change their lane according to the probability *ch*. Here, the lane-changing probability is defined according to the type of vehicle (slow or fast) and to the lane (lane 1 or lane 2). In this paper, only the symmetric case is adopted which means that there is no preference in one lane over another lane or the fast vehicle has a higher probability of lane changing. The *ch* is the probability of lane-changing for both types of vehicles from lane 1 (lane 2) to lane 2 (lane 1).

In real traffic, the bottleneck strongly affects the quality of traffic flow nearby it. In our model we considered two types of bottlenecks namely, moving, and fixed. Slow-moving vehicles are considered as a moving bottleneck. Hence, to mimic the fixed bottlenecks in our model, we consider a L_B site in the lattices that present an obstacle where both lanes are reduced to one as shown in Fig 1.

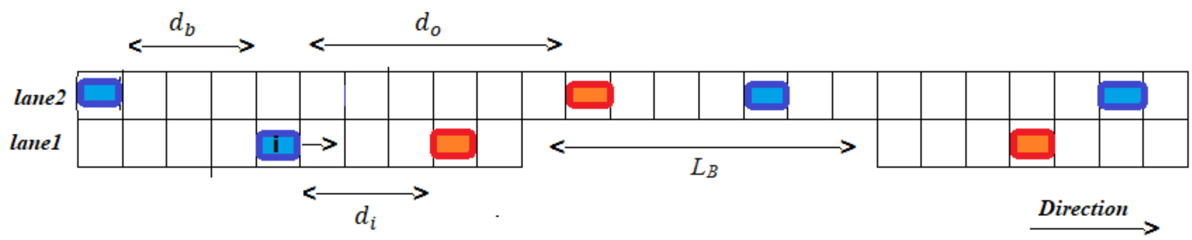


Fig. 1. The sketch of the model the blue color represents the fast vehicles while the red color denotes the slow vehicles

2.3 Rear-end collision.

A rear-end collision occurs when a moving vehicle hits another vehicle that has suddenly stopped or slowed down in front of it, both traveling in the same direction. For this we use the model proposed by Boccara et al [44] that consider the probability of the rear-end collision in a single lane CA model, where the conditions for an accident to occur are:

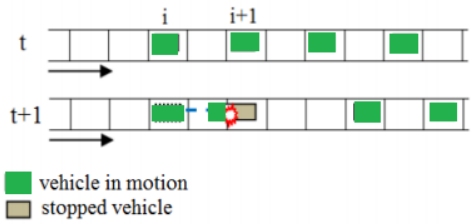


Fig. 2. Rear-end collision

1) **:** $d_i(t) \leq v_{max}^{(f\ or\ s)}$: where the number of empty sites in front of the *i-th* vehicle is less than the maximum speed of vehicles (fast or slow).
2) : $v_{i+1}(t)>0$**:** the vehicle ahead is moving.
3) : $v_i(t+1)=0$**:** the vehicle ahead stops in the next iteration.

These high-risk situations are computed and used as indicators of a potential rear-end collision with a probability of p'. It's crucial to emphasize that vehicles do not actually collide in our analysis. Instead, we quantify those specific high-risk events.

2.4 Lane-changing collision

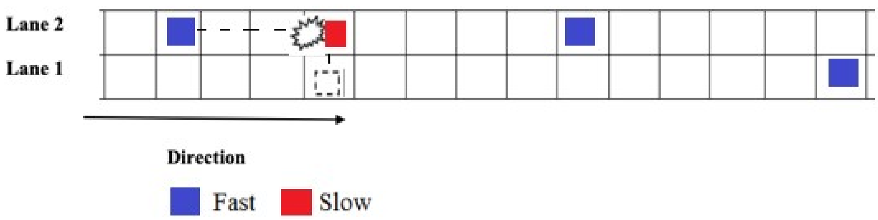


Fig. 3. Lane-changing collision

On the other side, In the two lanes traffic the collision can be induced by the unsafe lane-changing of the vehicles, where vehicles attempt to change their original lane and collide with the vehicle following it on the same lane (i.e., when the vehicles do not respect the safety criteria of the lane-changing). In this proposal our investigation considers this type of collision. Therefore, we will consider two types of collision namely, rear-end and lane-changing collision. We should note that the accident does not occur really in our system instead of that we have just calculated the probability of an accident occurring. The probability of the lane-changing collision to occur is computed if the following rules are fulfilled:

- Incentive criterion
- $d_o(t) > d_i(t)$.
- $d_b(t) < v_e(t+1)$.

Here v_e is the expected speed of the coming vehicle of the destinated lane (i.e the hoping lane for the vehicle that want to improve it speed by lane-changing, here this vehicle can collide with the coming vehicle in the hopping lane).

If the above conditions are achieved, a vehicle will cause an accident with a probability p''. Then we measured the traffic collision by calculating the probability of accident which defined as follows:

$$P_{acc}^{R\ or\ L} = \frac{1}{T}\frac{1}{N}\sum_{t=t_0}^{t_0+T} n_i(t) \quad (1)$$

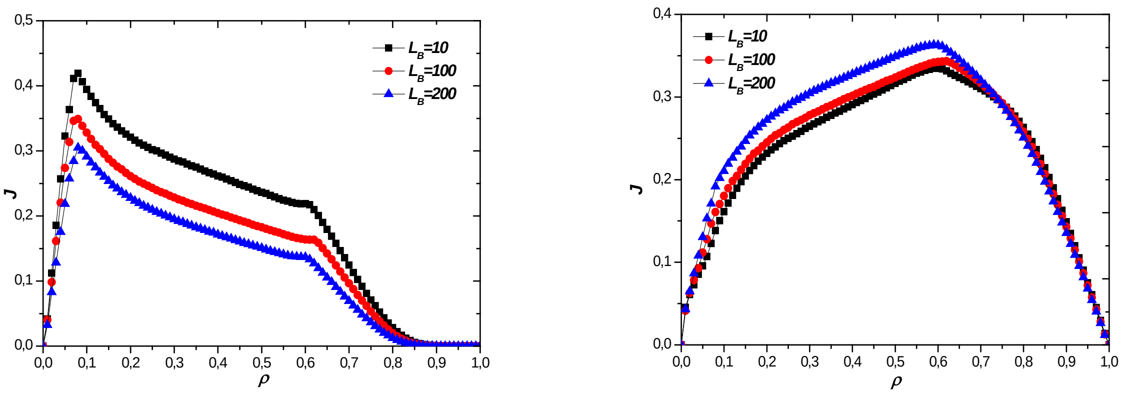
With:

P_{acc}^{R} (P_{acc}^{L}) refers to the probability of rear-end collision (lane-changing collision).
N : is the total number of vehicles (if we compute the P_{acc}^{R} , *N* denotes the number of vehicles in the same lane).
t_0: is the time after which the calculation is carried out.
T : is the calculation time.
$n_i(t) = 1$ if all the conditions of the accident are met, otherwise $n_i(t) = 0$.

3 RESULTS AND DISCUSSION

In this section, we investigate the influence of slow-moving vehicles and stationary obstacles on traffic flow and the probability of car accidents in both lanes. Our study focuses on a two-lane road, with each lane comprising 1000 sites. All vehicles have a braking probability of *p* = 0.2 and a lane-changing probability of *ch*=1. A dangerous situation is defined as when all conditions for an accident are present which has the potential to result in a rear-end or lane-changing collision. The respective probabilities for these collisions are p' =0.01 and p'' =0.01. The traffic composition is heterogeneous, consisting of two types of vehicles differentiated by their top speeds: $v_{max}^{f} = 5$ for fast vehicles and $v_{max}^{s} = 3$ for slow ones. The proportion of slow vehicles is f_s=0.2 while that of fast vehicles is f_f =1-f_s=0.8. The systems run for 60000 time-steps. The calculation is done for the last 10000-time steps with 100 independent simulations.

Two primary defects can impact traffic flow: slow-moving vehicles, treated as moving defects, and bottleneck zones, viewed as static defects. It's recognized that bottlenecks intensify the formation of slow vehicle groups and compress the free space ahead of them, akin to the Bose-Einstein condensation at low temperatures [45]. The stationary disruption can trigger an emergent phenomenon, which is a jam stemming from the deceleration of vehicles that locally reduces traffic flow. For clarity in this paper, we will refer to the dynamic disruption as 'slow vehicles' and the stationary disruption as 'bottleneck.'



(a) (b)

Fig. 4. Fundamental diagrams for several lengths of the bottleneck where (a): lane1, (b): lane2

In our computational analysis, the mixture of both defects is considered (slow vehicles and bottleneck) in the same system. Initially, we examine the throughput in both lanes with the presence of bottlenecks and slow vehicles. Fig. 4 shows the fundamental diagram for different values of bottleneck length L_B. For the lane 1, where the bottleneck is sited, the current J increases rapidly as the density ρ increases until it reaches a maximum value, then it starts decreasing slightly. For high density, the current starts decreasing rapidly until its value becomes zero. For lane 2, the current augments with the density until a maximum value then it drops. Here, the increase of L_B reduces (increase) the current in lane 1 (lane 2).

As we know the interaction between the two lanes is induced by the lane changing of vehicles. Therefore, to understand the variation of the throughput in both lanes it is better to illustrate the lane-changing frequency. Fig. 5 depicts the lane-changing frequency as a function of the density for different values of L_B. The curves of lane-changing frequency show similar features, it reveals that there is a rapid increase in the lane-changing frequency until its maximum value then starts decreasing gradually, beyond ρ =0.75 it becomes zero. The effect of lane-changing is only presented in the density range 0 to 0.75, A notable observation is that the frequency of lane changes is highest when the bottleneck length, L_B, is short. This can be attributed to the reduced distance between vehicles as the bottleneck length increases, making it challenging to find an adequate gap for a lane change, subsequently leading to a decrease in lane-changing frequency. For the case of ρ > 0.75, the lane-changing becomes impossible, therefore, the current is determined only by the longitudinal interaction. In this case, for lane 1 the value of the current becomes zero because of the obstruction of the bottleneck; the vehicles get trapped in this lane. However, for lane 2, lane-changing is not possible for all vehicles, therefore the order of vehicles remains the same, and for those range of densities, the slow and fast vehicles were forced to reduce their speed. The value of the current remains the same for lane 2 even if the size of the bottleneck in the other lane is reduced.

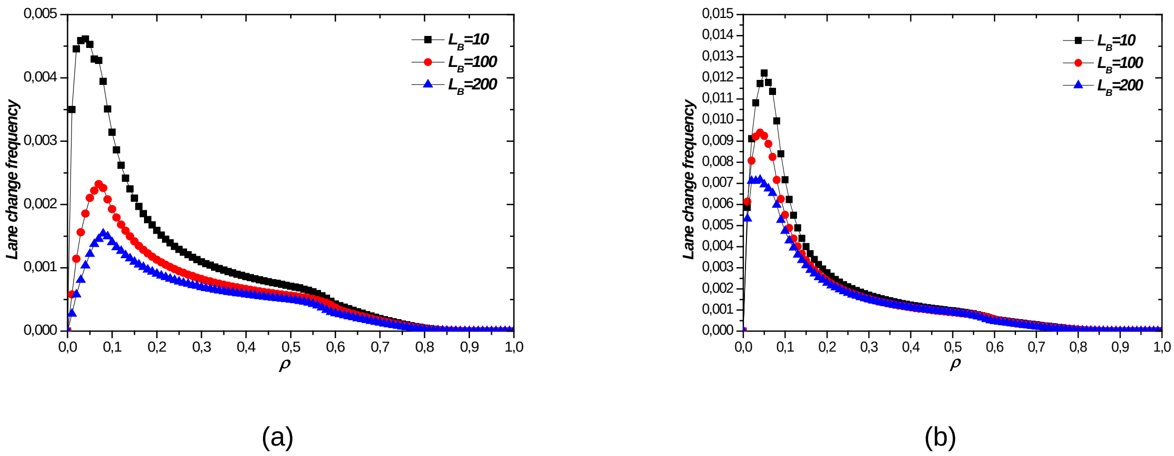


Fig. 5. Lane change frequency against the total density of vehicles, where (a): from lane1 to lane2, (b): from lane 2 to lane 1

To delve deeper into the bottleneck's impact on traffic characteristics, we examine the space-time configuration in Fig. 6. At lower densities, traffic flow in lane 1, where the bottleneck is located, is predominantly controlled by fast vehicles. In contrast, slow vehicles are primarily seen in lane 2. As vehicles near the bottleneck, they shift lanes, aiming to maintain their preferred speed. Given the ample free spaces at these lower densities, slow vehicles tend to remain comfortably in lane 2. Fast vehicles, however, behave differently. Initially, they switch to lane 2 to avoid the bottleneck's obstruction. Once past the bottleneck region, they revert to lane 1 to avoid the slower vehicles dominating lane 2.

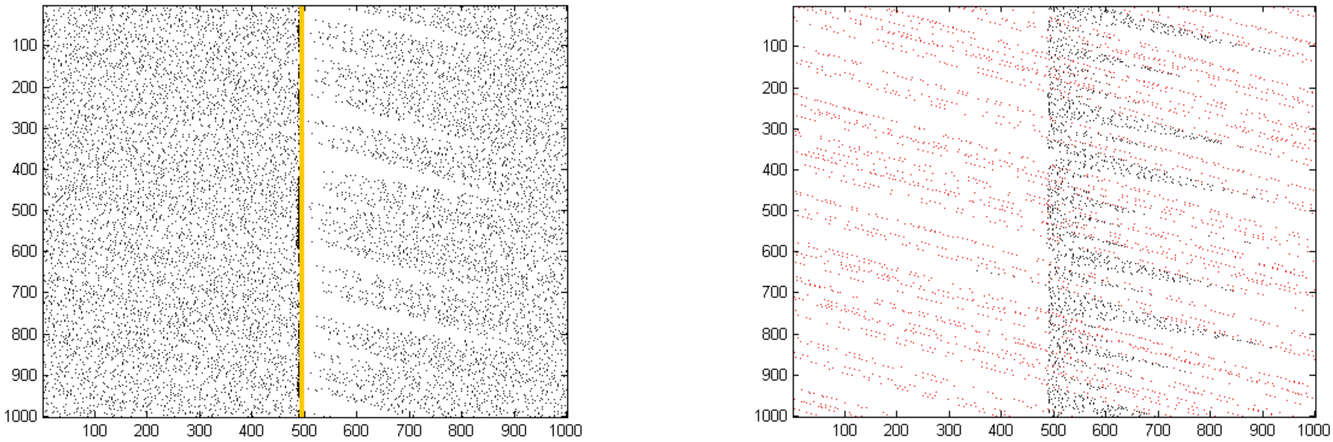
As density increases, the queue of stopped vehicles increases, worsening conditions in both lanes. The congestion forming behind the bottleneck in lane 1 intensifies, spanning the entirety of the lane. In this scenario, lane-changing from lane 1 to lane 2 diminishes, as safety criteria are often unmet. Concurrently, the bottleneck impedes the flow in lane 1, creating a more considerable gap ahead of it in the same lane. If the bottleneck's length, L_B, extends, it locally decreases vehicle density, akin to conditions in lane 2. This phenomenon is due to the bottleneck area restricting lane changes; vehicles in lane 2 can't shift to lane 1. As a result, vehicles in lane 2 move in clusters at uniform speeds. Upon approaching the bottleneck's end, they can transition to lane 1, capitalizing on the available space created by the bottleneck's obstruction. This movement aids in alleviating traffic congestion in lane 2, even at peak densities.

The spacetime configuration reveals that the bottleneck significantly influences traffic flow in both lanes. On one side, it concentrates the available space ahead of it. This obstruction in lane 1 creates more room, facilitating lane changes for vehicles in lane 2 and reducing their number. Conversely, as density rises, the queue of halted vehicles grows. In a two-lane model, the bottleneck is a localized issue. The combined presence of both bottlenecks and slow-moving vehicles can pose severe traffic challenges, including potential accidents.

Hereafter, the vehicle accident was studied, both types of accidents were considered (rear-end collision and the collision due to unsafe lane-changing).

Let's examine the probability of rear-end collisions as illustrated in Fig. 7. At extremely low densities, P_{acc}^{R} is zero in both lanes since all vehicles can maintain their desired speeds, even with a bottleneck. As the density increases, bottlenecks introduce minor disturbances in both lanes, slowing vehicles down. Consequently, stopped vehicles emerge, increasing rear-end collision risks. The collision probability reaches its maximum peak before decreasing. At this point, the number of halted vehicles in both lanes is significant. In lane 1, at high densities, the probability of rear-end collisions drops to zero due to a gridlock caused by the bottleneck and the inability to change lanes. In lane 2, at both low and high densities, the rear-end collision probability remains unaffected by the bottleneck length. For medium densities, the risk of car accidents decreases as the bottleneck lengthens.

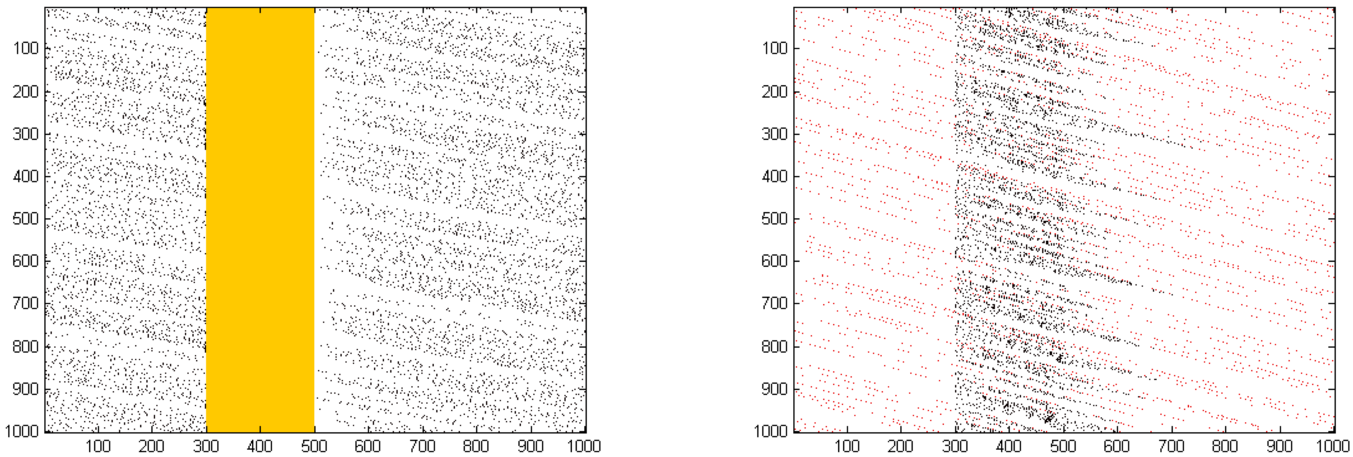
To delve deeper, we can refer to the speed frequency in both lanes for L_B=10 and L_B=200, as shown in Fig. 8. In lane 1, with L_B=10, there's a broad speed spectrum, indicating that while stopped vehicles exist, they do not dominate traffic. The speed variances in lane 1 for L_B=10 amplify the rear-end collision risks. Conversely, for L_B=200, even though the probability of stopped vehicles is higher (see Fig. 9), the extended bottleneck stabilizes speed fluctuations, thus reducing rear-end collision chances. Lane 2 presents a different scenario in both qualitative and quantitative terms. Here, the speed spectrum is varied for both L_B values. Since the bottleneck doesn't affect this lane directly, an increase in stopped vehicles heightens the risk of collisions.



Lane 1

Lane 2

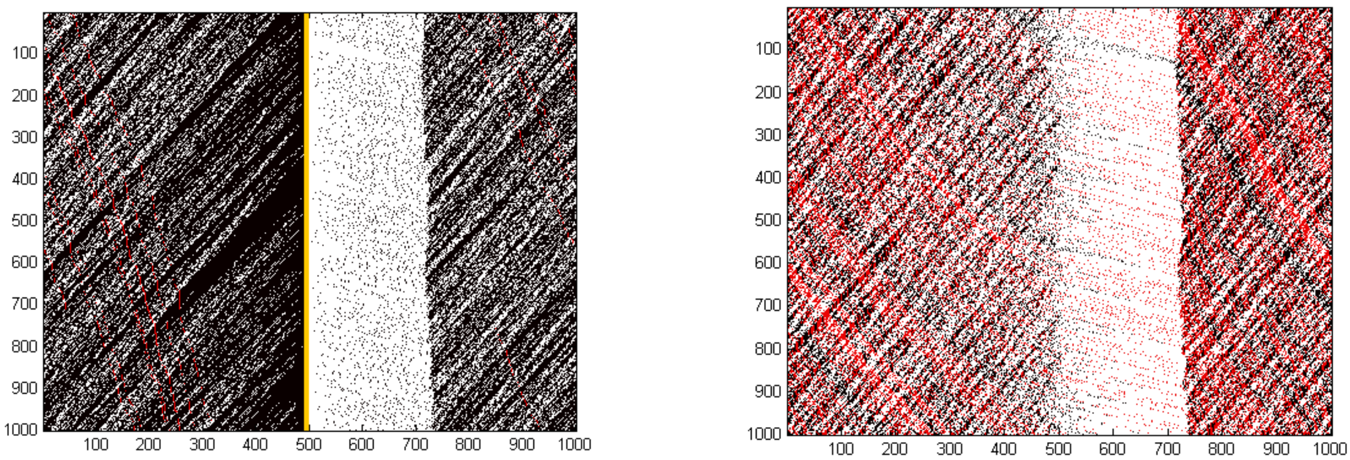
(a)



Lane 1

Lane 2

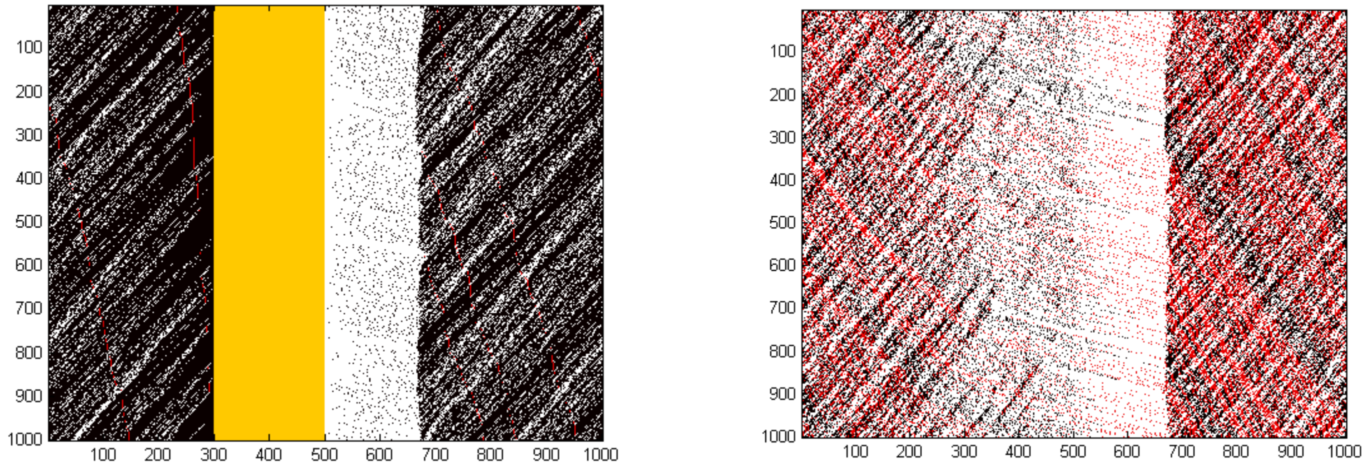
(b)



Lane 1

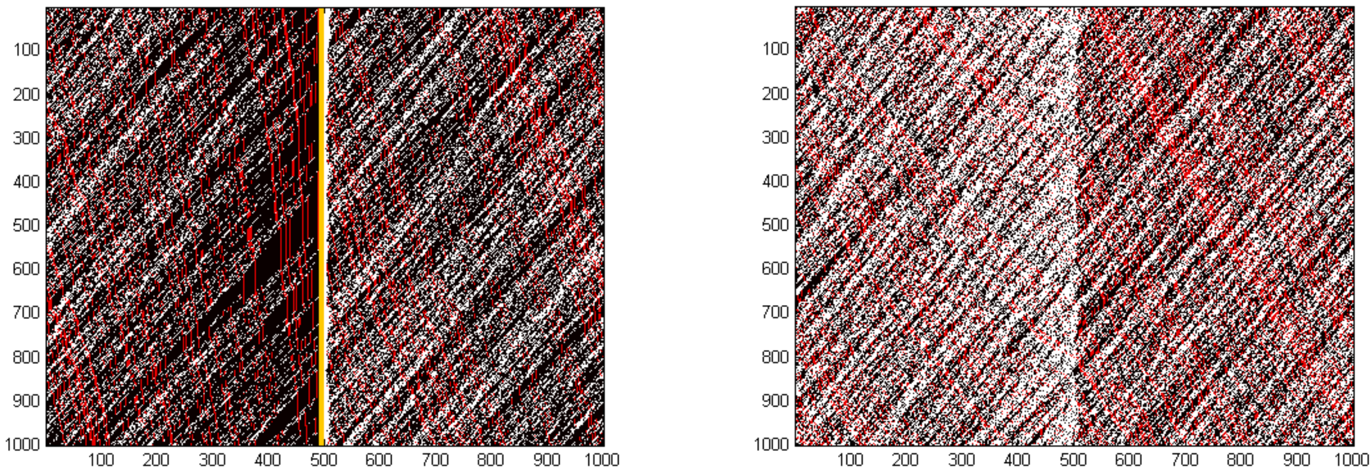
Lane 2

(c)



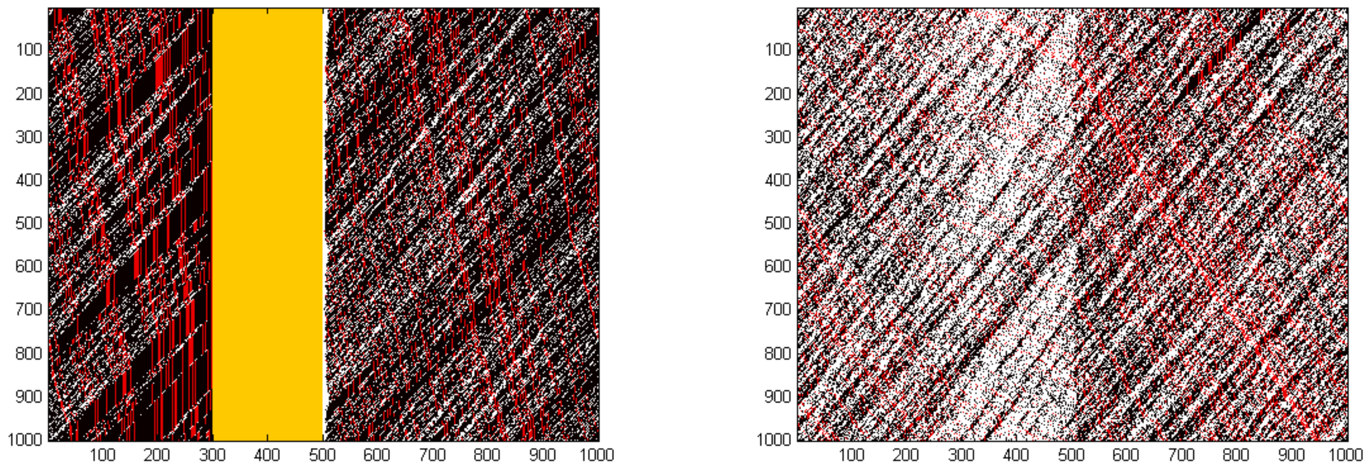
Lane 1 Lane 2

(d)



Lane 1 Lane 2

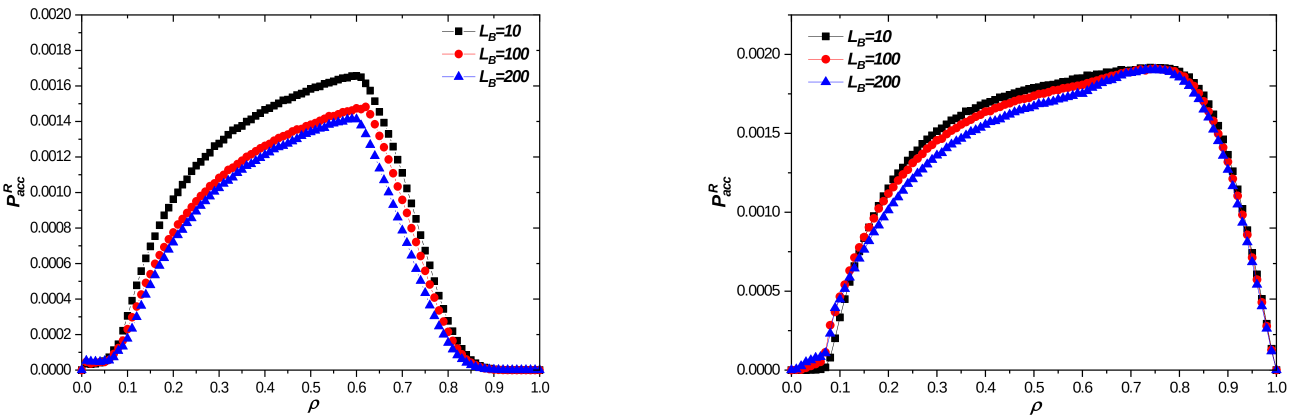
(e)



Lane 1 Lane 2

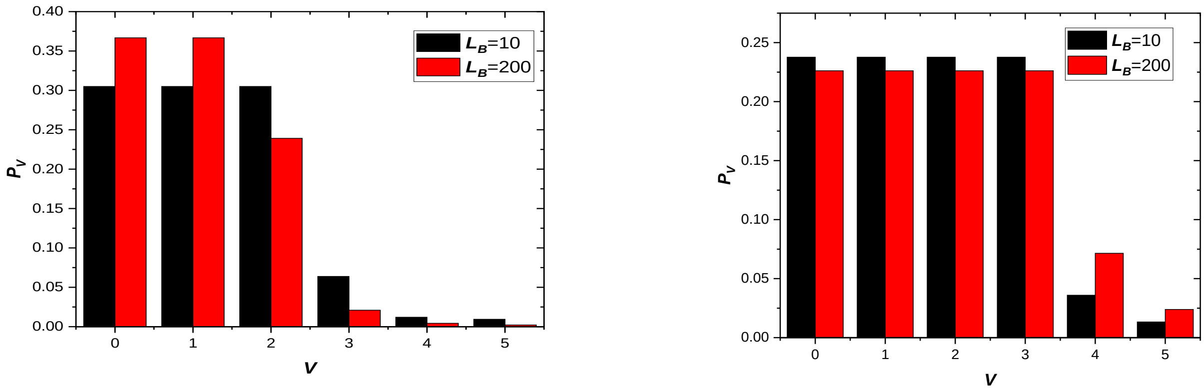
(f)

Fig. 6. Spacetime configuration for several values of LB a) LB=10, ρ=0.05 b) LB=200, ρ=0.05, c) LB=10, ρ=0.5 d) LB=200, ρ=0.5 , e) LB=10 , ρ=0.65 , f) LB=200 , ρ=0.65 (The white color represents the free space while the black color denotes the fast vehicles and the red color represents the slow vehicles, hence, the yellow color denotes the bottleneck). The horizontal axis represents the space where the evolution of space is from left to the right, while the perpendicular axis represents time, where the evolution of time is from up to down.



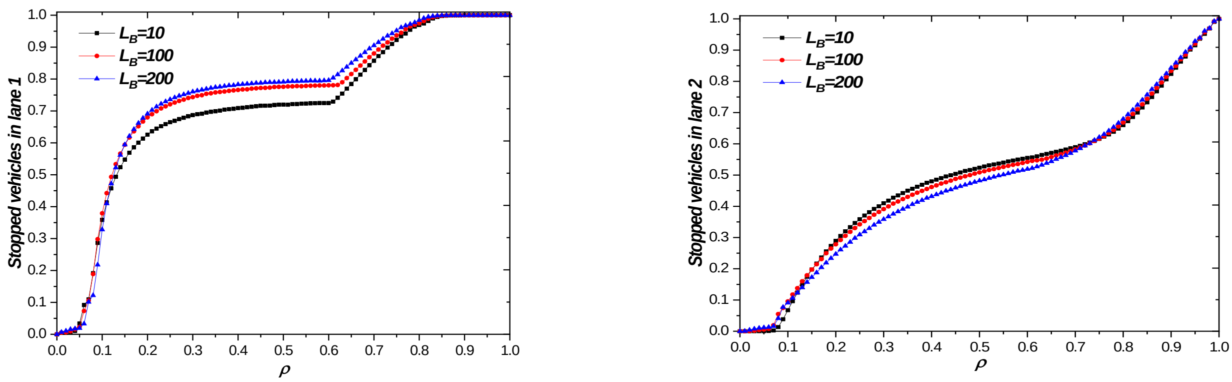
(a) (b)

Fig. 7. Rear end collision probability for a) lane 1, b) lane 2



(a) (b)

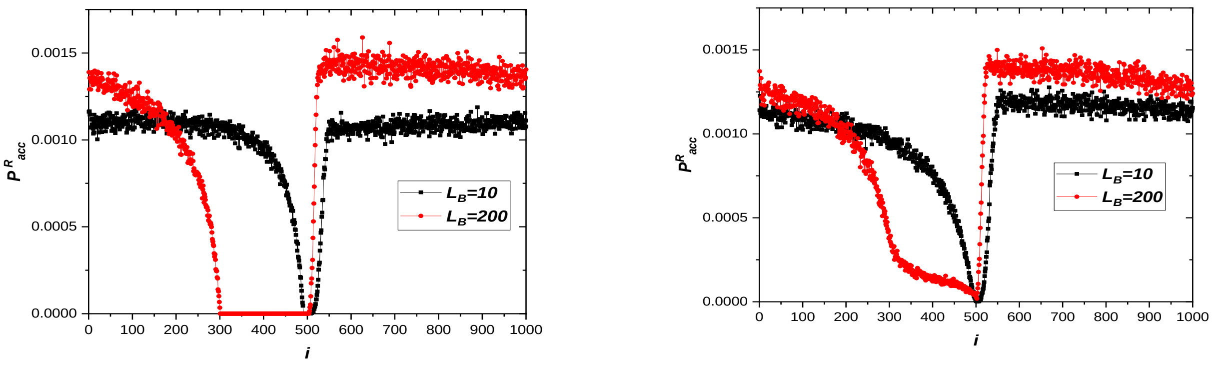
Fig. 8. Speed frequency for ρ=0.6 a) lane 1, b) lane 2



(a) (b)

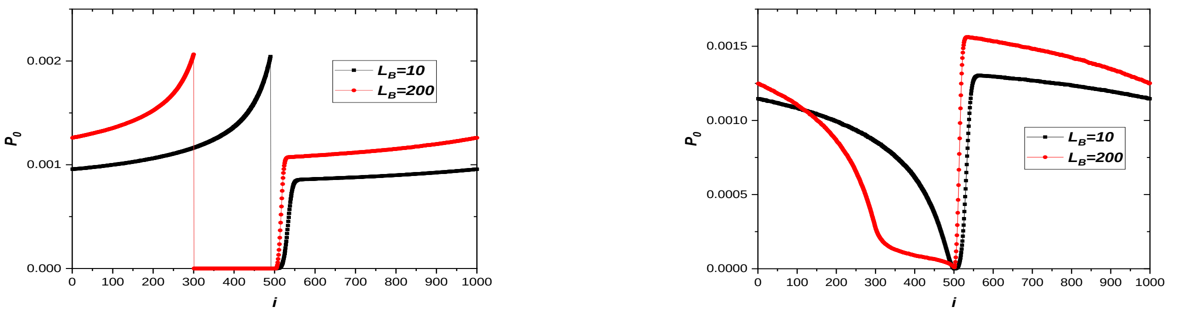
Fig. 9. Probability of stopped vehicles for several lengths of bottlneck and for a) lane 1 , b) lane 2

To gain a deeper understanding of the microscopic probability of vehicle accidents across the lane, let's examine the probability of vehicle accidents in relation to the lattice site, as depicted in Fig. 10. In lane 1, the probability of a vehicle accident decreases as we near the bottleneck. This suggests that as one approaches the bottleneck, the queue of halted vehicles stabilizes, as shown in Fig. 11. The presence of the bottleneck induces sporadic stops and starts at a distance from it (refer to the spacetime configuration in Fig. 6), elevating the probability of encountering a stationary vehicle closer to it, as illustrated in Fig. 11(a). Consequently, the probability of vehicle accidents decreases as one gets closer to the bottleneck. Conversely, in lane 2, the traffic density lessens as one approaches the bottleneck. The probability of coming across a stationary vehicle in zones immediately next to the bottleneck diminishes, as shown in Fig. 11(b). This decline in the number of halted vehicles correlates with a decreased probability of accidents near the bottleneck.



(a) (b)

Fig. 10. Profile of rear end collision probability for ρ=0.6 a) lane 1, b) lane 2



(a) (b)

Fig. 11. Pofile of stopped vehicles for ρ=0.6 a) lane 1, b) lane 2

The bottleneck influences vehicular accidents in both lanes, with rear-end collisions being highly dependent on its length. Now, let's examine collisions resulting from unsafe lane changes. Figure 12 depicts the probability of accidents due to such lane changes. As the density increases, the probability of collisions rises, peaking and then gradually decreasing to zero. These probability curves bear a resemblance to the lane-changing frequency graphs. The bottleneck length affects the ease with which vehicles change lanes. With a shorter L_B, vehicles change lanes more frequently since the chances of finding an appropriate gap are higher compared to a longer bottleneck scenario. Consequently, this increases the instances of critical situations that might lead to collisions.

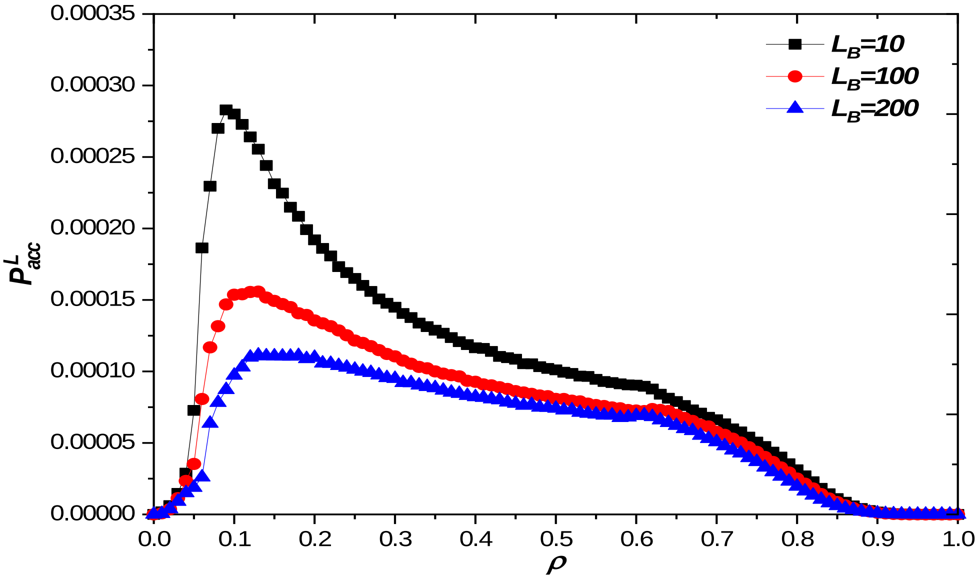


Fig. 12. Probability of vehicles collision due to unsafe lane-changing for several length of the bottleneck

4 CONCLUSIONS

In this study, we analyzed a two-lane traffic cellular automaton model with two distinct traffic hindrances: static bottlenecks (like work zones or lane reductions) and dynamic bottlenecks (slow vehicles such as trucks, buses, or caravans, etc.). Our objective was to comprehend how these elements interact and influence both traffic flow and safety. For traffic flow, we examined how the length of the static bottleneck affected traffic in each lane. Notably, at low densities, slow vehicles moved towards the lane without a static bottleneck, leaving the other lane predominantly to faster vehicles. These faster vehicles would then shift to the bottleneck-free lane to avoid slow vehicles and return to the bottlenecked lane once past them. At high densities, the lane with the static bottleneck saw its traffic flow drop until it was completely standstill. Interestingly, the length of the bottleneck didn't affect traffic flow on either lane within this high-density range. Regarding safety, we focused on the potential for rear-end and lane-change collisions. Generally, as the static bottleneck lengthened, the probability of rear-end collisions decreased due to the increase in stationary vehicles, which reduced the probability of collisions. Similarly, finding ample space for lane changes became challenging, leading to fewer lane changes and thus a reduced chance of related accidents. Our microanalyses also revealed that as vehicles neared a bottleneck, the risk of accidents diminished. The queued stationary vehicles became a stabilizing factor, causing fewer stops and starts further away from the bottleneck. However, as traffic thickened, the static bottleneck's size became a major determinant of both traffic flow and safety. At the highest densities, the risk of rear-end collisions in the lane with the static bottleneck was virtually nullified by gridlock. In conclusion, our findings offer valuable insights for traffic planners and engineers aiming to enhance road safety, especially in areas where lane reductions occur.

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