Mechanism of Traffic Jams at Speed Bottlenecks

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Abstract

In the past 20 years of complexity science, traffic has been studied as a complex system with a large amount of interacting agents. Since traffic has become an important aspect of our lives, understanding traffic system and how it interacts with various factors is essential. In this paper, the interactions between traffic flow and road topology will be studied, particularly the relationship between a sharp bend in a road segment and traffic jams. As suggested by Sugiyama[1], when car density exceeds a critical density, the fluctuations in the speed of each car will lead to greater fluctuations in speed of the cars behind it. This enhancement of fluctuation leads to the congestion of vehicles. Using a cellular automata model modified from Nagel-Schreckenberg Cellular Automata model[2], the simulation results suggest that the mechanism of traffic jam at bottlenecks is similar to this. Instead of directly causing the congestion in cars, bottleneck on roads only causes the local density of traffic to increase. The resultant congestion is still due to the enhancement of fluctuations. Results of this study opened up a large number of possible analytical studies that could be used as grounds for future works.

Keywords:

1 Introduction

In the past 50 years, the scientific community has proposed various traffic models in its attempt to understand vehicular traffic flow[3]. There are continuous fluid dynamical methods such as the Lighthill-Whitham theory in the 1950s, and Navier-Stokes-like momentum equation; discrete models such as the follow-the-leader model; as well as stochastic discrete models such as the Nagel-Schreckenberg Cellular automata models. Regardless continuous or discrete, deterministic or stochastic, the purpose of these models is to shed light on the physics of traffic flow and to provide predictions of various traffic phenomena.

Typical to most complex systems, traffic flow may be affected by various factors. This factors are topology, seasonal increase in road demand, signaling lights, weather, etc. Understanding how each of these factors affect the traffic flow is essential in avoiding undesirable phenomena,

such as massive traffic jams. The 2010 China National Highway 110 traffic jam had vehicles stuck in a jam for 10 days, originated from a traffic bottleneck due to road works coupled with the increase in vehicular density of the highway.

In Singapore, a new highway - the Marina Coastal Expressway (MCE) - was open in December 2013[4]. On the 2nd day of its operation, an extremely rare gridlock jam occurred from late morning to early afternoon. In a press release issued by the Land Transport Authority (LTA) of Singapore, this gridlock jam is attributed to the presence of a sharp bend as well as the merging of lanes on various segments of the highway. Traffic slowed down at this sharp bend, resulting in an effect known as the speed bottleneck. Hence, are traffic jams directly caused by the bottleneck mechanism? Or does bottleneck induce congestion, leading to traffic jams? In this paper, the Nagel-Schreckenberg (NaSch) cellular automata (CA) model will be applied to simulate the effects of a sharp bend on a highway traffic flow. With this, we hope to shed light on the mechanism of traffic jam formation at speed bottlenecks.

In a series of papers, Sugiyama[5, 1] used both experimental and simulation methods to explain the mechanism of traffic jams without bottlenecks. Using a continuous uniform road, he provided experimental evidence that the trigger of traffic jams is the critical limit of car density[1]. For any roads, small fluctuation in speed always exists between cars. If the vehicular density is high, the interaction between cars enhances these fluctuations, leading to large speed differences between them. This speed difference bunches up slow moving cars into a traffic jam clusters. The paper further states that bottlenecks only push the density beyond this critical limit, and that the mechanism of traffic jam formation at bottlenecks is the same as one without bottlenecks. The plan of this paper is to provide simulation evidence for this claim.

The physical mechanism of the formation of traffic jam at bottlenecks will be studied by implementing a speed bottleneck based on the effects of a sharp bend using a CA model of a highway traffic flow. We hypothesize the traffic bottleneck serves only to increase the density of cars in its locality. The mechanism of traffic jams that occurs at these points is the same as one that occurs in a high density traffic without bottlenecks. This is studied by comparing traffic jam clusters that are formed with and without traffic bottlenecks, to understand the mechanism behind the two different traffic jam formations. With that, the physics behind traffic jam formation due to a sharp bend will be discussed in this paper.

2   Simulation model and Preliminary results

2.1   Nagel-Schreckenberg Cellular Automata Model[2]

As mentioned earlier, the simulation of traffic flow will be done using the NaSch CA model. This model is a discrete stochastic model, whereby position, velocity, acceleration and time are discrete variables. For simplicity, the NaSch simulation is written for a 1-lane continuous road, in which sites of the model are written as a 1-D array with periodic boundary conditions.

The parameters of a typical NaSch simulation are:

Max Velocity, v_{max} - Maximum velocity of the cars

Density, c - No. of cars per unit road

Random Deceleration Probability, p - Probability that each car will decelerate by 1 per time step

In the NaSch model, the time evolution of the simulation is governed by a well defined prescription.

1. *Acceleration* - increase the speed of the car n if its velocity if lower than v_{max}

   $v_n \rightarrow min(v_n + 1, v_{max}),$

2. *Systematic Deceleration* - decelerate the vehicle to avoid collision with the vehicle ahead

   $v_n \rightarrow min(v_n, d_n - 1)$

where d_n is the distance between the car n and car $n + 1$

3. *Random Deceleration* - decrease the velocity of car n by 1 with a probability

   $v_n \rightarrow max(v_n - 1, 0)$ with probability p

4. *Movement*

   $x_n \rightarrow x_n + v_n$

Even though the NaSch simulation simplifies real world traffic into a handful of variable and simple evolution rules, the success of it is the reproduction of the fundamental diagram(figure 1). The fundamental diagram is essentially the flow-density relation of a given road[6].According to Chowdhury(2000)[3], the density at which the flow is maximum divides the solution into 2 phases - free flow phase and congested phase.

In our study, we ran the NaSch simulation with the following parameters:

Maximum Velocity, $v_{max} = 6$

Random Deceleration, $p = 0.2$

Road Length, $L = 1000$

Simulation Time, $t = 1000$

From these parameters, the fundamental diagram of the simulation is plotted in Figure 1

In Figure 1, the traffic flow at density $c = 0.10$ is higher than that of density $c = 0.40$. The solution at $c = 0.10$ is defined to be in the free flow phase and the solution at $c = 0.40$ in the congested phase[3].

Figure 2 and Figure 3 are the space-time distribution plots of the simulations which were ran at $c = 0.10$ and $c = 0.40$ respectively. The general features were observed in these two figures are found in similar studies using the NaSch simulations [2]. We have also observed traffic jam clusters in Figure 3.

2.2   Preliminary Results with Modified NaSch Model

As mentioned in section 1, the NaSch simulation model will be modified by adding a speed bottleneck which simulates the effect of a sharp bend. The primary effect of a sharp bend on a highway is that it will put a limit to the cars' speeds, which are lower than the average speed of most cars travelling on a straight path. Our speed bottleneck is then simulated by a velocity gate, which ensures that all vehicles passing through it are under a prescribed speed limit. This modification is done by adding the following into the NaSch simulation:

$dist = gate - j$
$if\ dist < v_{max}\ and\ dist > 0$
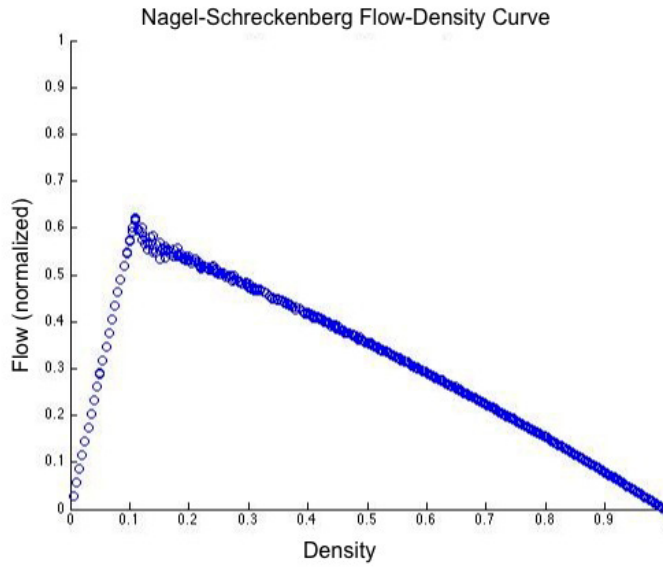$vmax \rightarrow min(v_{decel}, dist)$

Figure 1: Fundamental Diagram of NaSch Simulation which shows the flow-density relation of the simulation. Parameters of the simulation is as stated above
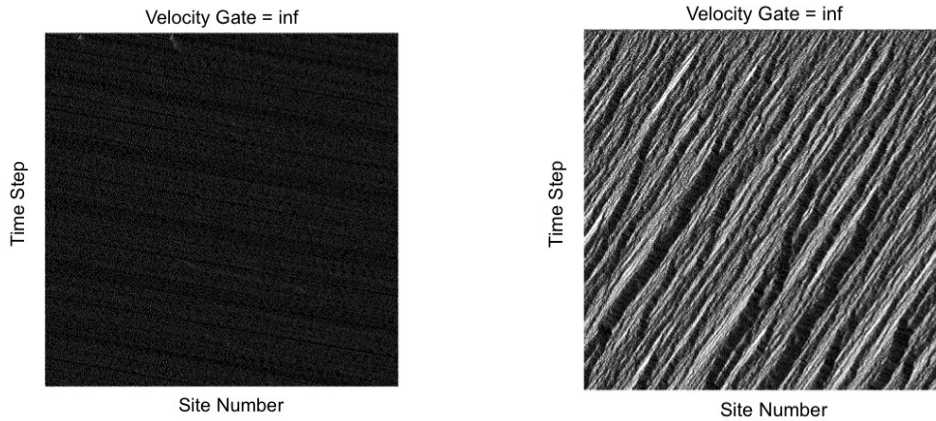

Figure 2: Space-Time distribution of NaSch Simulation. Density $c = 0.10$

Figure 3: Space-Time distribution of NaSch Simulation. Density $c = 0.40$

where $gate$ is a chosen point in the simulation, j is the index of the position of the car in consideration and v_{decel} is the speed limit of the gate.

The simulation is then modified with the addition of the velocity gate by the following parameters:

Position of Velocity Gate, $gate = 500$

Speed Limit of Gate, $v_{decel} = 1$

With the modified NaSch simulation, the space-time distribution is plotted in figure 4 for $c = 0.10$. As the velocity gate is set to slow down traffic, the results are as expected, i.e. congestion was induced in the locality upstream of the velocity gate.
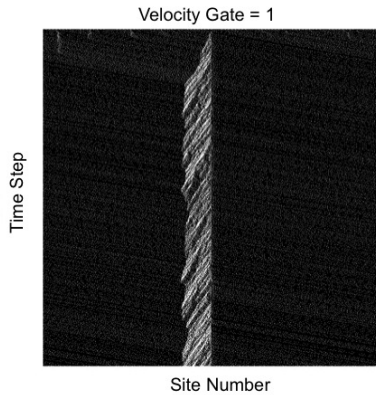

Figure 4: Space-Time distribution of modified NaSch simulation. Velocity gate added at site = 500, Density $c = 0.10$
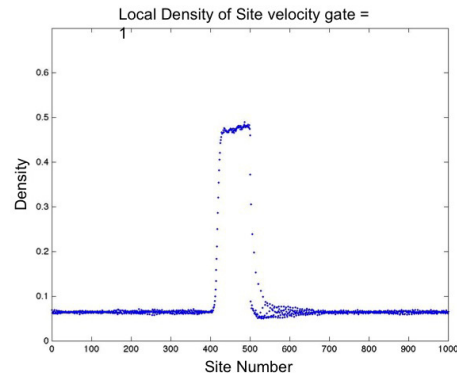
Figure 5: Local density distribution modified NaSch simulation. Velocity gate added at site = 500, Density $c = 0.10$

To understand how density changes due to speed bottlenecks, the distribution of the time-averaged occupancy[7] across the sites is plotted in Figure 5. As seen in Figure 5, with the addition of the velocity gate, there is a disparity between the density of the locality of the bottleneck, and the density of the other segments of the road. We see an average of $c = 0.10$ at most sites and $c \approx 0.48$ upstream of the velocity gate.

From figure 1, that is ran with the same parameters, we can see that for $c = 0.10$, the flow is in the free flow regime. For $c = 0.48$, the flow is classified as a congested regime. This suggests that the speed bottleneck does cause the region near it to have an increased vehicular density. More importantly, comparing Figure 4 with Figure 3, the congestion seen before the velocity gate at $c = 0.10$ has a similar form as the $c = 0.40$ case without the velocity gate.

The preliminary results seem to be consistent with our hypothesis - the presence of a speed bottleneck does increase the local density of the traffic flow. Furthermore, the local density falls into the regime of the congested phase of a NaSch simulation of similar parameters (Figure 1), and that the traffic jam clusters shown in Figure 4 and Figure 3 are similar. Nevertheless, there is need for a stronger indication of the similarities between the traffic jams with and without bottlenecks.

3   Comparing Traffic flow With and Without Bottlenecks

3.1   Relation to Sugiyama's Experiment

In Sugiyama's experiment[1], there is a relatively uniform backward velocity of the traffic jam cluster which was measured to be approximately $20km/h$. In the paper by Schreckenberg et al.(1993)[8], the formation of traffic clusters (jams) propagates backwards to the traffic flow was discussed for the general case of a NaSch simulation (without any modifications). More importantly, the characteristic of this backward propagating velocity is that it is independent of the density c and depends only on the random deceleration probability p.

The following is a logical argument which shows a positive correlation between the dependence of the cluster velocity on the parameters, and the mechanism of the traffic jam formation. As mentioned earlier, the formation of the traffic jams without bottleneck is driven by the fluctuations in the car velocities[1]. When the vehicular density is above the critical density, the speed fluctuation of the car in position i causes a greater fluctuation in the speed of car $i-1$ behind it. This propagation of speed fluctuation will lead to an enhancement of fluctuations, which ultimately lead to a traffic jam. When approaching a cluster, the systematic deceleration of car i will lead to the decceleration of car $i-1$ which translates to the backward velocity of the traffic jam cluster. The higher random deceleration probability of car i will then correspond to an overreaction to the systematic deceleration due to traffic jam cluster, and propagates the speed fluctuation(traffic jam cluster) at a faster rate. Hence, one of the ways of comparing the mechanism of the traffic jam formation is by comparing the dependence of the cluster velocity on the simulation parameters - density, maximum velocity and random decceleration probability.

3.2   Measuring Jam Cluster Velocity

The NaSch simulation is ran with the following parameters:

Road Length, $L = 1000$

Simulation Time, $t = 1000$

Maximum Velocity, $v_{max} = 6$

Random Decceleration, $p = 0.2$

Density, $c = 1.6$

Position of Velocity Gate, $gate = 500$
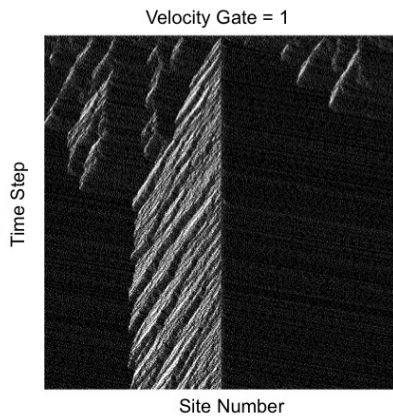
Speed Limit of Gate, $v_{decel} = 1$

Figure 6: Space-Time distribution of modified NaSch simulation. Velocity gate added at site = 500, Density $c = 0.16$
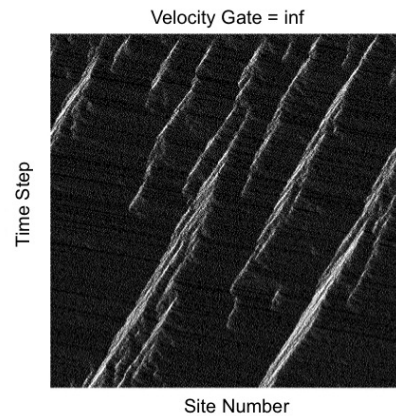
Figure 7: Space-Time distribution of NaSch Simulation. Density $c = 0.16$

With that, the space-time distribution of the simulation is plotted in Figure 6 and Figure 7, with and without the velocity gate respectively. The gradient of the line fitted to the traffic jam clusters is the backward velocities of the clusters.

The simulation is ran by varying c, v_{max} and p across a series of values, with and without the velocity gate. The measurement of backward velocity of the traffic jam cluster for each case is measured and the results are plotted in Figures 8, 10 and 9.
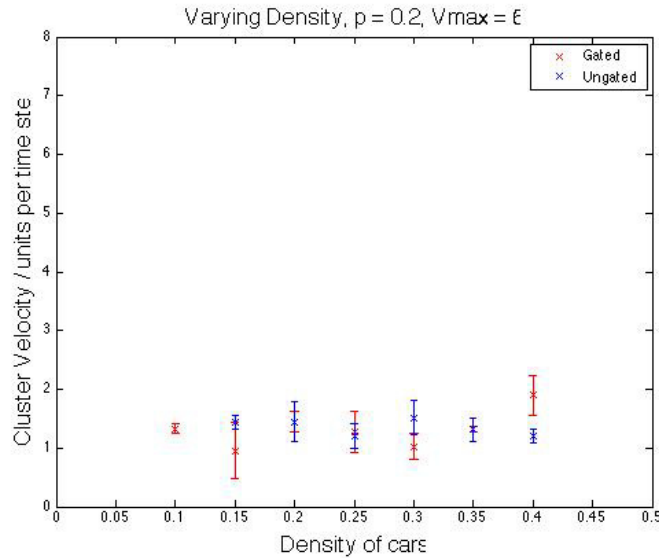

Figure 8: Cluster Velocity vs Density of cars. Data derived from measuring plot of the space-time distribution of simulation of varying road density

Figure 8, 10 and 9 shows that regardless of the bottlenecks in the system, the velocity of the traffic jam cluster remains dependent only on the random deceleration probability, and it is relatively independent of Vmax and density. Furthermore, Figure 10 suggests that functional relation between p and the cluster velocity is the same. However, without further analysis of the functional relation between them, this cannot be ascertained.

From the comparison between the dependence of the cluster velocity on the parameters with and without bottlenecks, it is likely that the mechanism of the formation of traffic jams is similar. This finding affirms our hypothesis that the formation of traffic jam at the speed bottleneck is due to the interaction of cars at a high density region. The speed bottleneck only causes the local density near it to increase, which triggers the interaction for traffic jams.

4   Future Work

The result of these studies has been linked specifically to the mechanism of traffic jams at a speed bottleneck. It has also opened up various possible studies that can be done in the future.

- The findings in this study shows that the traffic jam mechanism is independent of the bottlenecks - the formation of traffic jams are due to the interactions between cars, not the interactions of the cars with the bottleneck mechanisms. By using other variants
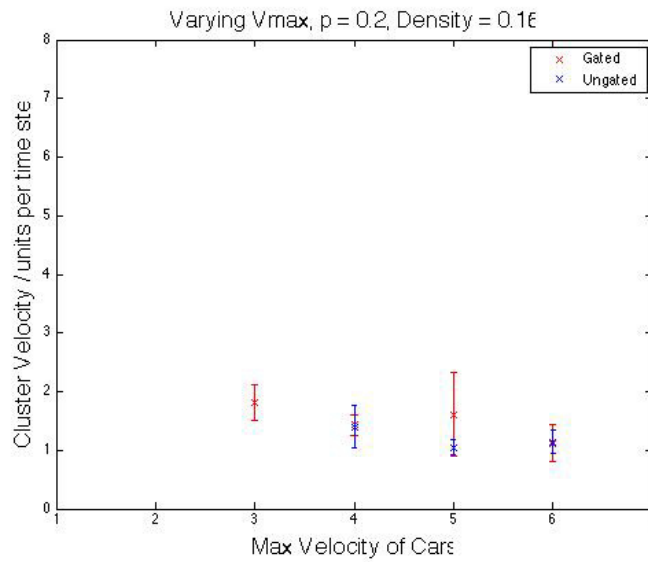
Figure 9: Cluster Velocity vs Vmax. Data derived from measuring plot of the space-time distribution of simulation of varying Vmax
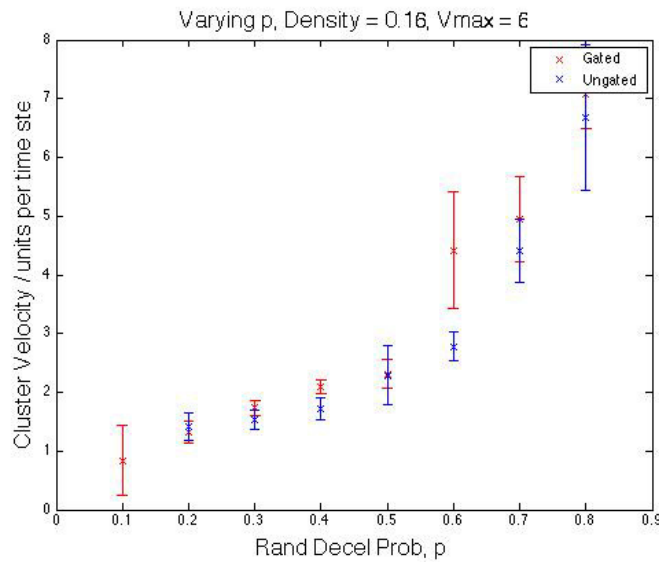

Figure 10: Cluster Velocity vs Random Deceleration p, Data derived from measuring plot of the space-time distribution of simulation of varying random deceleration parameter

of traffic bottlenecks, we can study whether all bottlenecks only lead to increases the local density, and does not cause traffic jams directly. Furthermore, the mechanism of bottlenecks increasing the local density can be further studied analytically.
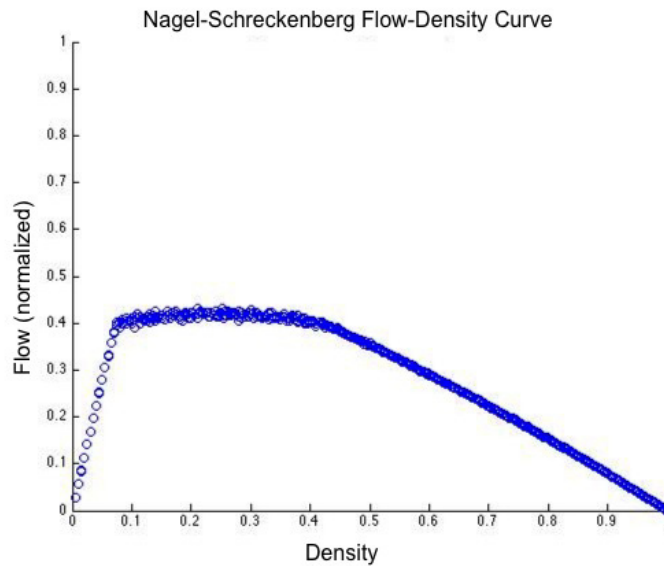
Figure 11: Fundamental Diagram of NaSch Simulation which shows the flow-density relation of the modified NaSch simulation. Parameters of the simulation is as stated above

- There is also a resemblance between the dependence on the random deceleration probabilities between the 2 cases (Figure 10). This can be better understood if there is an analytical relationship between the random deceleration parameters and the cluster velocities. However, no literature was found pertaining to this concept.

- In this study, we have also observed that microscopically, there is a similarity between the NaSch simulation with and without bottlenecks. However, by plotting their fundamental diagrams of the 2 cases(Figure 11) and Figure 1), we found that there is a macroscopic difference in the two systems. Similar to studies done by Schreckenberg et al.(1993), the overall effect on this presence of a speed bottleneck is creating an upper bound to the maximum allowed flow of the system. Further analysis of this macroscopic difference in the systems may provide deeper insights to the similarity and differences of these two cases.

5 Conclusion

Traffic jams is an undesirable traffic phenomena. In Singapore's Marina Coastal Expressway(MCE) traffic jam, affected drivers' time spent could translate to monetary loss and decreased productivity. Should this become a frequent occurence, there will be economic consequence to the nation. Hence, the understanding of the way traffic flow is affected by the topology of the road is important for a country's land authorities. In this paper, traffic jams at bottlenecks have been studied, and the focus was particularly on speed bottlenecks formed by bends on traffic highways, which was one of the causes of the MCE traffic jam in December, 2013.

Sugiyama's 2008 paper[1] covered the physical mechanism behind the formation of traffic jams without traffic bottlenecks. Comparing the similarities of jams with and without bottle-

necks suggests that the physical mechanism of the traffic jams at bottlenecks and the traffic jams that arises spontaneously is the same. Furthermore, it is likely that the physical mechanism of the bottlenecks solely serves to increase the local density of cars and does not affect the traffic jam mechanism of the system. However, to substantiate this claim, further studies has to be done on the various types of traffic bottlenecks.

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