Investigation of Traffic Dynamics Considering Driver's Characteristics and Downstream Traffic Conditions

Nikita Madaan and Sapna Sharma

Abstract This paper aims to examine the impact of the driver's behavior with the downstream average flow on current traffic dynamics in the lattice hydrodynamic model. The influence of driver's behavior and downstream traffic conditions with different sites are examined theoretically with the help of linear stability. It is observed that traffic flow stability can be improved by incorporating both driver's behavior and the average flow of traffic downstream. Finally, numerical simulations show that present traffic dynamics may be improved by integrating the impacts of driver behavior and average downstream traffic conditions in order to alleviate traffic congestion. Also, it validates the theoretical findings.

Keywords Traffic flow · Lattice model · Downstream average flow · Driver's behavior

1 Introduction

Travel has now become a vital part of most people's daily lives. The rising economy and growing population have also increased congestion in metropolitan areas. To alleviate crowded road conditions while incurring minimal traffic expenditures, management agencies have prioritized transportation security and dependability. Since traffic congestion is rising, some scholars have used mathematics and physics to explain why it occurs and to anticipate how it will evolve through modeling and simulation.

In recent decades, a lot of research has been carried out to resolve the urban traffic issues. Multiple traffic flow models, such as microscopic [3, 4, 35–37] and macroscopic [1, 2, 5–9, 9–34] models have been created to better understand the intricate process of congested roadways. Macroscopic models represent the flow of

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traffic by simulating the movement of liquids or gases and explore the overall average behavior of vehicles, whereas microscopic models are discrete models that simulate the individual behavior of vehicles.

Nagatani [5] created the fundamental one-lane unidirectional lattice hydrodynamic model (LHM) in 1998 by integrating characteristics of both microscopic and macroscopic models. This model allowed researchers to investigate the effect of real-world traffic conditions on traffic dynamics. Later, in real traffic flow, numerous different versions of Nagatani's lattice model were explored by investigating various aspects, including optimal current difference [13], driver's behavior [11], density difference effect [8] and, and so on. In addition, the lattice hydrodynamic one-lane unidirectional model is also expanded to include the curved road, two-lane, higher-dimensional lattice model in traffic systems [9, 16, 18–34].

In real-world traffic scenario, the intelligent transportation system (ITS) has been widely used in information and communication systems, making traffic information accessible to drivers in ITS environments more useful than ever before. In 1999, Nagatani [9] introduced a modified car-following model that includes interaction between the next-nearest-neighbor in front. Further, a car-following model is introduced by Kuang et al. [35] based on the effect of average headway. Later, Kuang et al. [34] modified the Zhu et al. model [36] by including the impact of average velocity as well as mean expected velocity field of forwarding vehicles in a vehicle to vehicle interaction. Subsequently, Chuan et al. [37] investigated the impact of multi-anticipation and also examined the influence of forwarding sites in the LHM. Later, Zhu et al. [17] developed a single-lane LHM that took into account the difference between optimal and real traffic flow, based on average density and prior traffic flow.

In regular traffic situations, driver characteristics (timid, aggressive, and normal) have a significant effect on traffic flow. Additionally, numerous studies [11, 12, 14, 15, 18, 19, 29] have been conducted to examine the impact of the behavior of drivers on traffic flow. According to studies, aggressive drivers create a strong impact on the stability of traffic flow, although timid drivers are found to have a negative influence on traffic flow stability. For this reason, it's more realistic to investigate traffic features in terms of the behavior of drivers.

The future era is of semi-automated vehicles. These vehicles partially depend on the information of the surroundings as well as downstream situations. The idea of this paper is to improve the traffic conditions by taking the driver's behavior with the average flow of front sites simultaneously. Therefore, the aim is to create a new lattice model that incorporates average flow on front sites and the behavior of drivers on current traffic conditions.

The following is the outline of the paper. The proposed lattice model, which incorporates the influence of downstream average flow and behavior of drivers on current traffic conditions, was described in Sect. 2 of this paper. Section 3 explains the proposed model's theoretical analysis. Section 4 contains the findings. Section 5 contains the conclusion.

2 Model

Nagatani [5] developed the basic LHM in 1998 to depict the density waves in traffic flow. The basic lattice model consists of two equations: a continuity equation and a flow evolution equation, as follows:

$$\partial_t \rho_j(t) + \rho_0(\rho_j(t)v_j(t) - \rho_{j-1}(t)v_{j-1}(t)) = 0, \tag{1}$$

$$\partial_t(\rho_j(t)v_j(t)) = a[\rho_0 V(\rho_{j+1}(t)) - \rho_j(t)v_j(t)]. \tag{2}$$

Here, ρ_j denotes the density and v_j presents the velocity, respectively at jth site on the one-dimensional lattice for time t. The average density is ρ_0, while a is the sensitivity of the drivers. $V(\rho_{j+1})$ is the Bando's [3, 4] optimal velocity function (OVF), given as

$$V(\rho) = \frac{v_{max}}{2}\left[\tanh\left(\frac{2}{\rho_0} - \frac{\rho}{\rho_0^2} - \frac{1}{\rho_c}\right) + \tanh\left(\frac{1}{\rho_c}\right)\right], \tag{3}$$

In Eq. (3), ρ_c and v_{max} denote the critical density and maximum velocity, respectively. In reality, drivers constantly analyze the state of the road ahead of them and attempt to adjust their vehicle's speed in response to the information received from ITS. Further, to explore the traffic situations more realistically, we propose a LHM to examine the driver's behavior while taking into account downstream average flow on forward sites. Thus, the continuity equation is the same in the new LHM, but the flow equation is reformed as

$$\partial_t(\rho_j v_j) = a\Big[\rho_0 V(\rho_{j+1}) - \rho_j v_j + \alpha(2p-1)\tau V'(\rho_{j+1})\partial_t \rho_{j+1}\Big] + \lambda\Big[q_j^{avg} - \rho_j v_j\Big]. \tag{4}$$

The delay time is given by $\tau = 1/a$, and the anticipation coefficient is denoted by α in Eq. (4). The parameter $p \in [0, 1]$ demonstrates that how the behavior of the drivers impacts the traffic dynamics. Whenever $p < 0.5$, the driver exhibits the timid behavior; when $p = 0.5$, it exhibits normal behavior; and whenever $p > 0.5$, it exhibits aggressive behavior. Average flow difference is represented by λ and $q_j^{avg} = \frac{1}{n}\sum_{l=1}^{n}(\rho_{j+l}v_{j+l})$ is the average flow of the n forward sites.

After omitting v from Eqs. (1) and (4), the resulting density evolution equation be obtained as

$$\partial_t^2(\rho_j) + (\lambda + a)\partial_t \rho_j - \frac{\lambda}{n}\left(\sum_{l=1}^{n}\partial_t \rho_{j+l}\right) + a\alpha\rho_0^2\tau(2p-1)[V'(\rho_{j+1})\partial_t\rho_{j+1} - V'(\rho_j)\partial_t\rho_j] + a\rho_0^2\Big(V(\rho_{j+1}) - V(\rho_j)\Big) = 0. \tag{5}$$

In the new model, when $\alpha = 0$ or $p = 1/2$ with $n = 1$, it reduces to the Tian et al. model [7]. Furthermore, this model is identical to Nagatani's [5] model with $\alpha = 0$ or $p = 1/2$ and $\lambda = 0$.

3 Theoretical Analysis

To examine qualitative features of proposed LHM, we apply linear stability analysis. Consider a traffic flow with a constant density of ρ_0 and an optimal velocity of $V(\rho_0)$. As a result, traffic uniformity may be achieved by

$$\rho_j(t) = \rho_0, \quad v_j(t) = V(\rho_0), \tag{6}$$

where $V'(\rho_0) = \frac{dV(\rho)}{d\rho}\mid_{\rho=\rho_0}$. After adding a tiny fluctuation $(y_j(t))$ into the condition of smooth flow of traffic, i.e., $\rho_j(t) = \rho_0 + y_j(t)$ and using modified density in Eq. (5). Applying linearization, we obtain

$$\partial_t^2 y_j + (\lambda + a)\partial_t y_j - \frac{\lambda}{n} \sum_{l=1}^{n}(\partial_t y_{j+l}) + a\alpha\rho_0^2 V'(\rho_0)\tau(2p-1)(\partial_t y_{j+1} - \partial_t y_j) + a\rho_0^2 V'(\rho_0)(y_{j+1} - y_j) = 0 \tag{7}$$

Now, in Eq. (7), we can describe the deviation $y_j(t)$ as an exponential function, i.e. $y_j(t) = exp(\iota\kappa j + \eta t)$, we get:

$$\eta^2 + (a+\lambda)\eta - \frac{\lambda}{n}\eta\Big(\sum_{l=1}^{n}(e^{ikl})\Big) + a\alpha\rho_0^2\tau(2p-1)V'(\rho_0)\eta(e^{\iota\kappa} - 1) + a\rho_0^2 V'(\rho_0)(e^{\iota\kappa} - 1) = 0. \tag{8}$$

On inserting $\eta = \eta_1(\iota\kappa) + \eta_2(\iota\kappa)^2...$ in Eq. (8), coefficients of $(\iota\kappa)$ and $(\iota\kappa)^2$ of the first and second order were obtained as follows:

$$\eta_1 = -\rho_0^2 V'(\rho_0), \tag{9}$$

$$\eta_2 = -\frac{\rho_0^2 V'(\rho_0)}{2} - \frac{(\rho_0^2 V'(\rho_0))^2}{a} - \frac{\alpha(\rho_0^2 V'(\rho_0))^2}{a} - \frac{\lambda\rho_0^2 V'(\rho_0)(n+1)}{2a}. \tag{10}$$

Homogeneous flow is uncertain for longer wavelength with $\eta_2 < 0$, but becomes stable with $\eta_2 > 0$. So, the neutral stability criterion is as follows:

$$a = -2\rho_0^2 V'(\rho_0)(1 - \alpha(2p-1)) - \lambda(n+1). \tag{11}$$

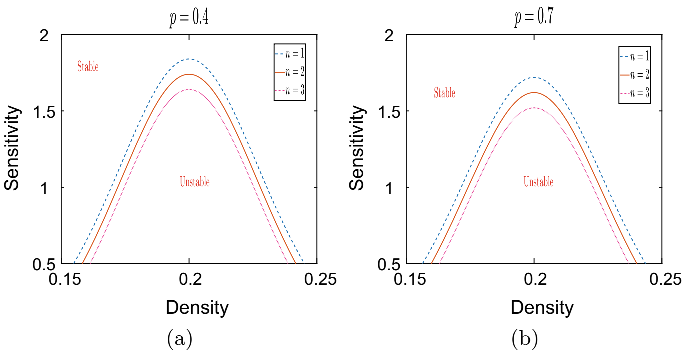


Fig. 1 Phase plot for distinct number of forwarding sites n in parameter space (ρ, a), when $\alpha = 0.1$ and $\lambda = 0.1$ **a** $p = 0.4$, **b** $p = 0.7$

The following criterion can be used to stabilize a uniform flow:

$$a > -2\rho_0^2 V'(\rho_0)(1 - \alpha(2p - 1)) - \lambda(n + 1). \tag{12}$$

Figures 1a–b show the phase plot for distinct number of forwarding sites (n) and p, while all other parameters remain constant in the parameter space (ρ, a). Figure 1 illustrates the neutral stability curves. The apex of each curve reflects the crucial point (ρ_c, a_c) in the respective curves. In this manner, the phase plot is separated into stable and unstable regions. As seen in Fig. 1a, the amplitude of neutral stability curves reduces as the number of forwarded sites (n) increases when $p = 0.4$, implying that the stability of uniform traffic flow has been improved by using downstream average flow information. Also, it can be seen in Fig. 1b, that the sensitivity decreases as n increases with $p = 0.7$, indicating the widening of the stability region. This demonstrates that by considering both impacts simultaneously, i.e., downstream average flow and effect of behavior of drivers on traffic flow can help in strengthening the traffic flow stability.

4 Numerical Simulation

Numerical simulation with periodic boundary conditions is used to verify theoretical results. The following initial conditions are preferred:

$$\rho_j(0) = \begin{cases} \rho_0; & j \neq \frac{M}{2}, \frac{N}{2} - 1 \\ \rho_0 - \sigma; & j = \frac{N}{2} \\ \rho_0 + \sigma; & j = \frac{N}{2} - 1 \end{cases} \tag{13}$$

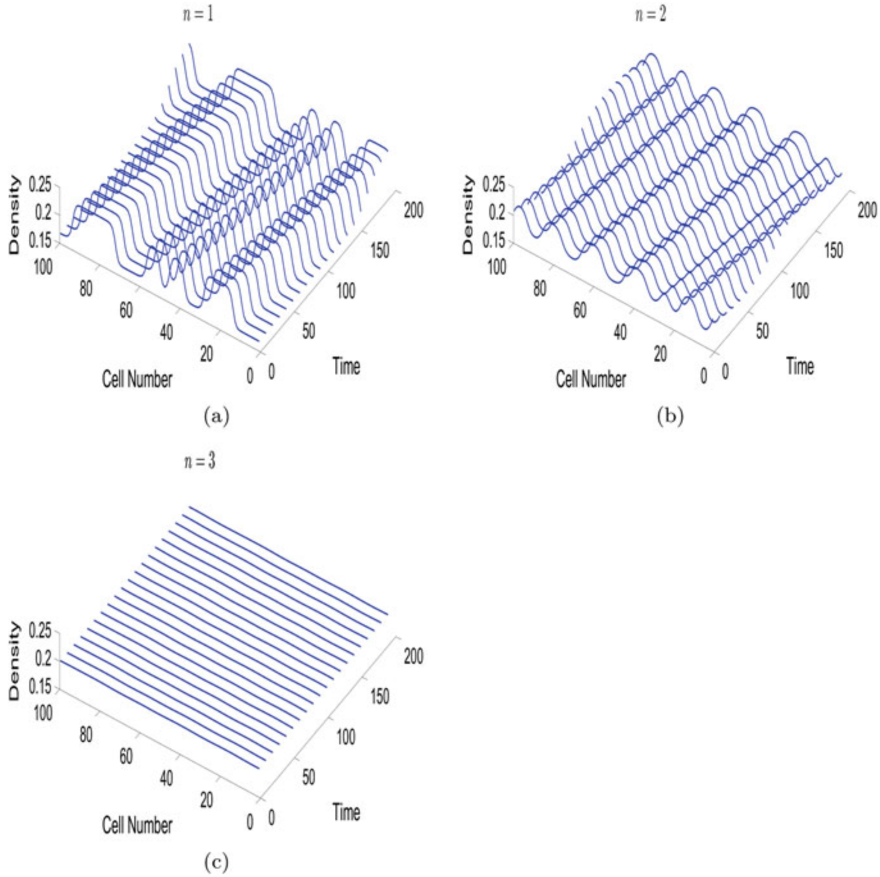


Fig. 2 When $a = 1.65$ and $p = 0.4$, the spatial-temporal evolution of density waves for distinct values of n

The associated variables are as follows: $\rho_0 = \rho_c = 0.2$, $\lambda = 0.1$, $v_{max} = 2$, $\alpha = 0.1$, and $t = 2 \times 10^4$ s. Here, $N = 100$ and $\sigma = 0.05$ represents the total number of sites and initial perturbation, respectively.

Figure 2 shows the space-time density wave for distinct values of forwarding sites (i.e., $n = 1, 2,$ and 3) at $t = 10^4$s, when $p = 0.4$, and $a = 1.65$. The density waves in the pattern of Fig. 2a, b are kink-antikink, since the stability requirement (Eq.(12)) is not met, and the flow goes from uniform to congested after the tiny disturbance. From the figures, one can observe that the kink-antikink density waves occurs for smaller values of n and propagates backwards. Further, when the value of n increases, stability region increases, especially for $n = 3$, the amplitude of density

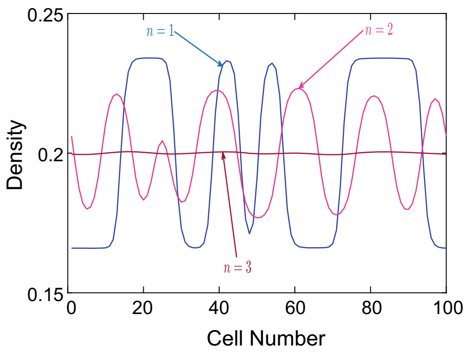


Fig. 3 Density patterns for distinct values of n at $t = 10000\,\mathrm{s}$ with $a = 1.65$ and $p = 0.4$

wave vanishes completely. We found that if forward lattices are more than 3, then also it satisfies the stability condition. It indicates that traffic congestion can be reduced by having information about forward lattices.

The density pattern for distinct values of n with $p = 0.4$ shown in Fig. 3, which corresponds to Fig. 2. As n increases, the density wave's amplitude reduces, and finally, the flow goes into the homogeneous steady state for $n = 3$.

Figure 4 indicates the spatio-temporal density wave profiles for distinct values of forwarding sites (i.e., $n = 1, 2,$ and 3) at $t = 10^4$s, when $p = 0.7$, and $a = 1.5$. The density waves in the pattern of Fig. 4a, b demonstrate that an initial perturbation results in the kink-antikink solution propagating backward direction. When the instability criteria (Eq.(12)) is fulfilled, the flow transits from uniform to congested. The amplitude of density wave diminishes with the increase in n, however, as $n = 3$, the stability region increases.

The density pattern for distinct values of n with $p = 0.7$ shown in Fig. 5, which corresponds to Fig. 4. As n increases, the density wave's amplitude reduces, and for $n = 3$, the amplitude of density wave vanishes completely, which shows that the knowledge of prospective sites flow can help in minimizing the traffic congestion.

After examining all the simulation findings, we noticed that all the simulation results are completely similar to the theoretical results presented in the previous section. Also, in real traffic phenomenon, it is feasible for the drivers to adjust their speed, if they have adequate information about the forward traffic situation and then the traffic congestion reduces. All these results show that the information about the diver's behavior and the downstream average flow on forward sites is crucial in improving traffic flow stability.

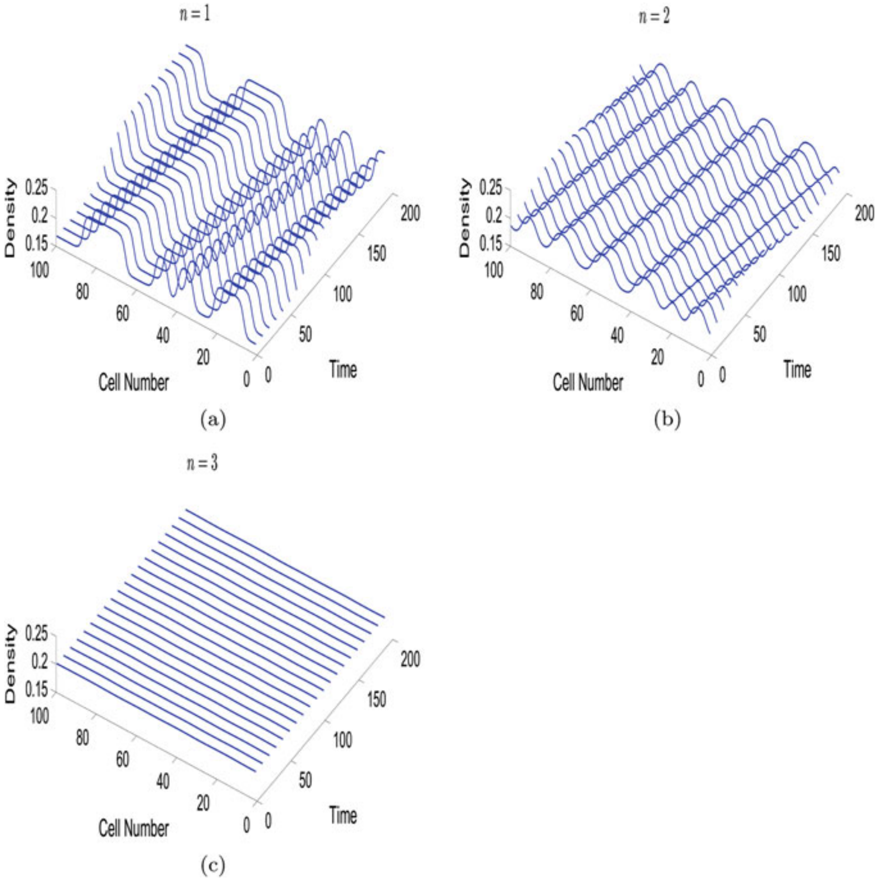
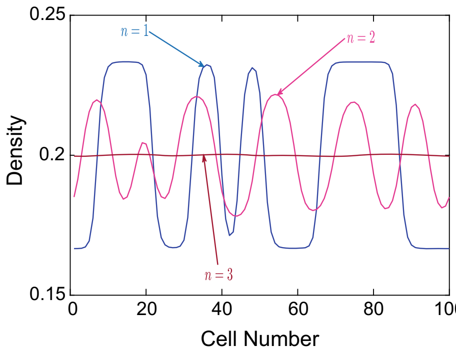


Fig. 4 When $a = 1.5$ and $p = 0.7$, the spatio-temporal evolution of density waves for distinct values of n

Fig. 5 Density patterns for distinct values of n at $t = 10000\,\mathrm{s}$ with $a = 1.5$ and $p = 0.7$



5 Conclusion

The current study presents a LHM for examining the influence of driver's behavior with downstream average flow on traffic dynamics. The stability condition of traffic dynamics is analyzed via theoretical analysis. From the study of the phase diagram, it is depicted that the new model considering the average flow of front sites with driver's behavior has a greater influence on reducing the traffic congestion than the basic lattice model. Furthermore, the numerical findings correspond well with the theoretical conclusions. Thus, it is prominent to make an aspect that the current traffic dynamics are influenced by the forward traffic information and it is favorable in reducing the traffic congestion.

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