Linear Stability and Nonlinear Analysis of an Extended Optimal Velocity Model Considering the Speed Limit

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Abstract
In this paper, an extended car-following model is proposed based on an optimal velocity model (OVM), which takes the speed limit into consideration. The model is analyzed by using the linear stability theory and nonlinear analysis method. The linear stability condition shows that the speed limit can enlarge the stable region of traffic flow. By applying the reductive perturbation method, the time-dependent Ginzburg-Landau (TDGL) equation and the modified Korteweg-de Vries (mKdV) equation are derived to describe the traffic flow near the critical point. Furthermore, the relation between TDGL and mKdV equations is also given. It is clarified that the speed limit is essentially equivalent to the parameter adjusting of the driver’s sensitivity.

Keywords
Optimal Velocity Model (OVM), Speed Limit, TDGL Equation, mKdV Equation

1. Introduction
With the development of social economy and the increasing number of motor vehicles, traffic jam has become the common bottleneck of urban development. The problem of traffic congestion can be attributed to the stability and solitary waves of traffic flow models. Generally speaking, traffic flow models have been divided into macroscopic models, microscopic models, and mesoscopic models according to the aggregation level. There are many microscopic models in traffic flow, and the most commonly studied model is the car-following model. The car-following model is a microscopic traffic flow model used to describe the behavior of a single driver. In order to study the complex characteristics of traffic
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flow, scholars have proposed various car-following models to understand the formation and transmission mechanism of traffic congestion.

The early research work on the car-following theory was originated from Reuschel [1] and Pipes [2]. Since then, scholars have carried out many related research works. In 1961, Newell [3] proposed a car-following model of velocity-governing equation by assuming that the velocity adjustment of the rear car depends on the optimized velocity of the headway. In 1995, Bando et al. [4] proposed the optimal velocity model (OVM), in which the optimal velocity was determined only by the headway with the forward vehicle. Despite the simplicity and few parameters, the OVM can be used to describe various characteristics of the actual traffic flow, such as stop-and-go phenomenon, the instability of traffic flow and the evolution of traffic jams. In 1998, Helbing and Tilch [5] verified OVM by using empirical data and proposed a generalized force model (GFM), which overcomes the problems of unrealistic deceleration and excessive acceleration of OVM. In 2001, Jiang et al. [6] found that the GFM could not be used well to describe the delay time and the kinematic wave speed at jam density and proposed a full velocity difference model (FVDM) by considering the influence of positive and negative speed differences on the car-following models. In 2008, in order to overcome the high deceleration of FVDM, Ge et al. [7] proposed a two-velocity difference model (TVDM) based on the application of intelligent transportation system (ITS). Recently, some new car-following models were submitted to describe traffic nature more realistically [8] [9] [10] [11] [12]. Undoubtedly, these scholars have made various contributions to the establishment and development of traffic flow. For the above car-following models, there have been many researches focusing on the stability and density waves in the past time.

In the past, more research has focused on the density waves for the car-following models. However, it is still enormous significance to derive thermodynamic theory of traffic flow model and to link traffic meta-stability with spinodal decomposition in first-order phase transition [13]. The TDGL equation can refer to non-equilibrium phase transition [14]. Nagatani [15] firstly proposed the thermodynamic theory of traffic flow, and derived the TDGL equation of two simple lattice hydrodynamic models near the critical point and the thermodynamic potential of traffic flow by applying the reduced perturbation method. So far, there has been little research on deriving TDGL equation from car-following models [16] [17] [18] [19]. Since the TDGL equation of the traffic flow model can be used to represent the thermodynamics theory of jamming transition, it is very important to establish the traffic flow model and derive the corresponding TDGL equation.

In recent years, traffic jams are still intense as the number of cars in big cities increases and road infrastructure becomes more complex. Exploitation of intelligent transport system is a part of the best ways for settling transport problems. Considering the influence of an intelligent transportation system, many researchers have established some car-following models to describe the real nature
of traffic flow [20] [21] [22] [23] [24]. In fact, intelligent vehicle navigation system can provide service for the vehicles, when the actual speed of the vehicle deviates from the speed limit. If the vehicle overspeeds, it is easy to cause traffic congestion and traffic accidents, and the driver can learn the speed limit information in advance, he can adjust in advance to achieve a stable speed. At this time, the traffic can develop smoothly. In other words, drivers’ knowledge of speed limit information in advance plays an important role in stabilizing the traffic flow. However, most of the car-following models have not considered the effect of the speed limit.

In order to reveal the effect of the speed limit on traffic flow, an extended optimal velocity model is introduced by considering the speed limit in this paper. The content of this paper is organized as follows. In Section 2, an extended optimal velocity model with consideration of the speed limit is introduced. In Section 3, the linear stability condition is obtained from the linear stability analysis method. In Section 4, the TDGL equation and its corresponding soliton solution are obtained from the reductive perturbation method. In Section 5, the mKdV equation is derived in the unstable region. In Section 6, conclusions are given.

2. An Extended OVM with Speed Limit

In 1995, Bando et al. [4] proposed the OVM based on the analysis of the characteristics of traffic flow. The equation of motion is as follows:

$$\frac{d^2\Delta x_n(t)}{dt^2} = a \left[ V(\Delta x_n(t)) - \frac{d\Delta x_n(t)}{dt} \right].$$  

(1)

where $a$ is the driver’s sensitivity coefficient, $x_n(t) > 0$ is the position of the vehicle at time $t$, $V(\cdot)$ is the optimal velocity function, and $\Delta x_n(t) = x_{n+1}(t) - x_n(t)$ represents the space headway between the car ahead and the car following at time $t$.

As people make full use of the latest information of the intelligent transportation system, some traffic problems are gradually solved. For example, intelligent vehicle navigation system uses computer and communication technology to provide information relevant to the cars on the road and generate dynamic traffic information, such as the speed limit [25]. It can determine at what appropriate velocity the driver should drive under the current conditions according to the current traffic conditions and signal status. When the actual velocity of the vehicle deviates from the speed limit by the navigation system, the driver will adjust the actual velocity according to the stable speed limit to improve the traffic capacity and relieve traffic congestion. Therefore, we propose the following extended optimal velocity model by considering the speed limit:

$$\frac{d^2\Delta x_n(t)}{dt^2} = a \left[ V(\Delta x_n(t)) - \frac{d\Delta x_n(t)}{dt} \right] + \lambda a \left( V_{\text{lim}} - \frac{d\Delta x_n(t)}{dt} \right),$$  

(2)

where $V_{\text{lim}}$ is the speed limit provided by the navigation system, and $\lambda$ de-
notes the reactive coefficient related to the speed limit \( V_{\text{lim}} \).

We chose the optimal velocity function \( V(\Delta x_a(t)) \) as proposing in reference [4].

\[
V(\Delta x_a(t)) = \frac{v_{\text{max}}}{2} \left[ \tanh \left( \frac{\Delta x_a(t) - h_c}{h_c} \right) + \tanh \left( \frac{h_c}{h_c} \right) \right],
\]

(3)

where \( v_{\text{max}} \) is the maximum velocity of the vehicles, \( h_c \) is the safety distance of the vehicles. The optimal velocity function \( V(\cdot) \) is a function of \( \Delta x_a(t) \), and it’s a monotonically increasing function with an upper bound.

For the convenience of analysis in the following, we discretize Equation (2) with asymmetric forward difference [24], and rewrite it in terms of headway as follows:

\[
\Delta x_a(t + 2\tau) = \Delta x_a(t + \tau) + \tau \left[ V(\Delta x_{a+1}(t)) - V(\Delta x_a(t)) \right] - \lambda \left[ \Delta x_a(t + \tau) - \Delta x_a(t) \right]
\]

(4)

where \( \tau \) is time step and \( \tau = \frac{1}{a} \).

### 3. Linear Stability Analysis

In this section, we study the extended optimal velocity model of Equation (4) by the method of linear stability analysis.

First, we assume that the initial state is stable, the headway of the vehicle is \( h \) and the corresponding optimal velocity is \( V(h) \). At this time, the vehicle position of the steady-state traffic flow can be expressed as

\[
x_c^0(t) = hn + V(h)t, \quad h = L/N,
\]

(5)

where \( N \) is the number of cars, \( L \) is the road length, and \( h \) is the average headway. Let \( y_a(t) \) be a small deviation from the steady-state solution \( x_c^0(t) \), then the perturbed solution is given as

\[
x_a(t) = x_c^0(t) + y_a(t).
\]

(6)

Substituting (6) into Equation (4), we obtain the following formulation:

\[
\Delta y_a(t + 2\tau) = \Delta y_a(t + \tau) + \tau V' \left[ \Delta y_{a+1}(t) - \Delta y_a(t) \right] - \lambda \left[ \Delta y_a(t + \tau) - \Delta y_a(t) \right].
\]

(7)

where \( \Delta y_a(t) = y_{a+1}(t) - y_a(t) \) and \( V'(h) = \frac{dV(\Delta x_a(t))}{dr}_{\Delta x_a=h} \).

Let \( \Delta y_a(t) = \exp(ikn + zt) \), Equation (7) can be rewritten as follows:

\[
e^{2z\tau} = e^{z\tau} + \tau V'(e^{z\tau} - 1) - \lambda (e^{z\tau} - 1).
\]

(8)

where \( V' = V'(h) \). Since \( z \to 0 \) as \( ik \to \infty \), \( z \) can be expressed by a long wave as \( z = z_1(ik) + z_2 \frac{1}{k^2} + \cdots \).

Substituting it into (8) and neglecting the higher order items, we obtain the coefficients of the first-and second-order term of \( ik \), as follows:

\[
z_1 = \frac{V'(h)}{1 + \lambda}, \quad z_2 = \frac{V'(h)}{2(1 + \lambda)} - \frac{V''(h)}{2(1 + \lambda)^2} \frac{1}{k^2}.
\]

(9)
Clearly, if $z_2$ is negative, the initial steady uniform flow will become unstable; if $z_2$ is positive, the original steady flow state remains unchanged. Thus, the neutral stability condition of an extended optimal velocity model considering the speed limit is obtained as follows:

$$\tau = \frac{(1 + \lambda)^2}{V'(h)(3 + \lambda)}. \quad (10)$$

We are concerned with $\tau$ relating to $\lambda$, the reactive coefficient relating to $V_{lim}$. Thus, the uniform traffic flow remains stable if the following condition holds:

$$\tau < \frac{(1 + \lambda)^2}{V'(h)(3 + \lambda)}. \quad (11)$$

As $\lambda > 0$, we have $1 < \frac{(1 + \lambda)^2}{3V'(h)(3 + \lambda)}$. This shows that the stable region of (11) is larger than that of (12) the OVM (where $\lambda = 0$) given as follows:

$$\tau < \frac{1}{3V'(h)}. \quad (12)$$

From (11), we can see that the parameter $\lambda$ has an important effect on the stabilization of traffic flow. Notice that $\left[\frac{(1 + \lambda)^2}{3 + \lambda}\right] > 0$, $\lambda > 0$, at this time, $\frac{(1 + \lambda)^2}{3 + \lambda}$ increases monotonically with respect to $\lambda$, so it holds that $\frac{1}{3V'(h)} < \frac{(1 + \lambda)^2}{V'(h)(3 + \lambda)}$, $\lambda > 0$. As a result, the stability condition (11) is weaker than (12), and the stable region is larger than OVM.

**Figure 1** shows the phase diagram in the $(h, a)$-phase where $h$ (meter) is the headway and $a$ (1/second) is sensitivity which corresponds to the inverse of the delay time. It shows the stable neutral lines of (10) with different values of $\lambda$, where $v_{max} = 2\text{ m/s}$ is taken as the maximal velocity and $h_i = 4\text{ m}$ is the safe distance. In **Figure 1**, above the neutral stability curve is a stable region, which represents a free phase without traffic congestion, and below the neutral stability curve is an unstable region, which represents the traffic jam phase that evolves backward as the density waves stop-and-go. The peak of each curve represents the critical point $(h_c, a_c)$. **Figure 1** also shows that as the sensitivity coefficient $\lambda$ to the speed limit increases, the stable region also gradually expands. This shows that if the driver can obtain the speed limit information through the intelligent vehicle navigation system in advance, he can adjust the vehicle speed earlier, effectively enhance the stability of the traffic flow, and avoid traffic congestion.

**4. TDGL Equation**

Now we use the long-wavelength modes to derive the TDGL equation for describing the pedestrian flow on a coarse-grained scale [26]. The long-wavelength
expansion is the simplest way to describe the behavior of the long-wavelength models.

First, we analyze the slow-varying behavior of long waves near critical point \((h_c, a_c)\). Introduce the slow scales \(\varepsilon\) of space variable \(n\) and time variable \(t\) [27], and define the slow variables \(X\) and \(T\) as follows:

\[
X = \varepsilon(n + bt), \quad T = \varepsilon^2 t, \quad 0 < \varepsilon \ll 1,
\]

where \(b\) is a constant. The headway \(\Delta x_n(t)\) is defined by

\[
\Delta x_n(t) = h_c + \varepsilon R(X, T).
\]

Next, by expanding Equation (4) to the fifth-order of \(\varepsilon\) with the use of (13) and (14). We obtain the expression:

\[
\varepsilon^2 h_c \partial_x R + \varepsilon^3 h_c^2 \partial_x^2 R + \varepsilon^4 \left[ \partial_x R + h_c \partial_x^2 R + h_c^2 \partial_x^3 R \right] + \varepsilon^5 \left[ h_c \partial_x R + h_c^2 \partial_x^2 R + h_c^3 \partial_x^3 R \right] = 0.
\]

Here, the coefficients \(h_i\) are given in Table 1. Where

\[
V'(h_c) = \frac{dV(\Delta x_n(t))}{d\Delta x_n(t)} \bigg|_{\Delta x_n = h_c}, \quad \text{and} \quad V'' = V''(h_c) = \frac{d^2V(\Delta x_n(t))}{d\Delta x_n^2} \bigg|_{\Delta x_n = h_c}.
\]

Now, we study the traffic flow near critical point \(\tau = (1 + \varepsilon^2) \tau_c\). By taking \(b = \frac{V'(h_c)}{1 + \lambda}\), we eliminate the second- and third-order terms of \(\varepsilon\) from Equation (15). The simplified equation of Equation (15) is as follows:

\[
\varepsilon^4 \partial_x R = \varepsilon^4 m_1 \partial_x^4 R + \varepsilon^3 m_2 \partial_x^3 R^3 - \varepsilon^5 m_3 \partial_x^5 R^3 - \varepsilon^4 m_4 \partial_x^4 R - \varepsilon^3 m_5 \partial_x^3 R^3.
\]

Here, the coefficients \(m_i\) are given in Table 2. By transforming variables \(X\) and \(T\) into variables \(x = \varepsilon^{-1} X\) and \(t = \varepsilon^{-3} T\), and taking \(S(x, t) = \varepsilon R(X, T)\), Equation (16) can be rewritten as follows:
Table 1. The coefficients $h_i$ of (15).

<table>
<thead>
<tr>
<th>$h_1$</th>
<th>$h_2$</th>
<th>$h_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b - \frac{\nu'}{1 + \lambda}$</td>
<td>$\frac{(3 + \lambda) \nu b'' - \nu'}{2(1 + \lambda)}$</td>
<td>$\frac{(7 + \lambda) \nu b'' - \nu'}{6(1 + \lambda)}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$h_4$</th>
<th>$h_5$</th>
<th>$h_6$</th>
<th>$h_7$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-\frac{\nu''}{6(1 + \lambda)}$</td>
<td>$\frac{1}{1 + \lambda} \frac{(3 + \lambda) \nu b'}{6}$</td>
<td>$\frac{(15 + \lambda) \nu b'' - \nu'}{24(1 + \lambda)}$</td>
<td>$-\frac{\nu''}{12(1 + \lambda)}$</td>
</tr>
</tbody>
</table>

Table 2. The coefficients $m_i$ of (16).

<table>
<thead>
<tr>
<th>$m_1$</th>
<th>$m_2$</th>
<th>$m_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{7 + \lambda}{6(3 + \lambda)} \nu'' - \frac{\nu''}{6(1 + \lambda)}$</td>
<td>$-\frac{\nu''}{6(1 + \lambda)}$</td>
<td>$\frac{(3 + \lambda) \nu b'}{2(1 + \lambda)} - \frac{\nu''}{2(1 + \lambda)}$</td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th>$m_4$</th>
<th>$m_5$</th>
<th>$m_6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{15 + \lambda(1 + \lambda) \nu''}{24(3 + \lambda)} - \frac{\nu''}{24(1 + \lambda)} + \frac{(7 + \lambda) \nu''}{6(3 + \lambda)} + \frac{\nu''}{6(1 + \lambda)} - \frac{\nu''}{12(1 + \lambda)}$</td>
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</tr>
</tbody>
</table>

\[
\partial_i S = m_i \Omega^3 x S + m_i \partial_i S^3 \left( \frac{(3 + \lambda) \nu V'}{2(1 + \lambda)^3} - \frac{1}{2(1 + \lambda)} \right) V' \partial_i^2 S - m_i \partial_i^4 S - m_i \partial_i^2 S^3. \tag{17}
\]

By adding term $V' \left[ \frac{(3 + \lambda) \nu V'}{(1 + \lambda)^3} - \frac{1}{1 + \lambda} \right] \partial_i S$ to both of the left-and right-hand sides of (17) and transforming $t_i = t$ and

\[
x_i = x - V'(1 + \lambda) \left[ \frac{(3 + \lambda) \nu V'}{(1 + \lambda)^3} - \frac{1}{1 + \lambda} \right] t \quad \text{in (17), we obtain}
\]

\[
\partial_i S = \left( \partial_i - \frac{1}{2} \partial_i^2 \right) \left[ \frac{7 + \lambda}{6(3 + \lambda)^2} - \frac{1}{6(1 + \lambda)} \right] V' \partial_i^2 S
\]

\[
+ V' \left[ \frac{(3 + \lambda) \nu V'}{(1 + \lambda)^3} - \frac{1}{1 + \lambda} \right] \left[ S - \frac{V'}{6(1 + \lambda)} S^3 \right]. \tag{18}
\]

We define the thermodynamic potentials:

\[
\phi(S) = \frac{1}{2} V' \left[ \frac{(3 + \lambda) \nu V'}{(1 + \lambda)^3} - \frac{1}{1 + \lambda} \right] S^2 + \frac{\nu''}{24(1 + \lambda)} S^4. \tag{19}
\]

By taking (19) into Equation (18), the TDGL equation becomes

\[
\partial_i S = - \left( \partial_i - \frac{1}{2} \partial_i^2 \right) \frac{\partial \phi(S)}{\partial S}. \tag{20}
\]

with

\[
\Phi(S) = \int dx_i \left[ \frac{1}{2} \left( \frac{7 + \lambda}{6(3 + \lambda)^2} - \frac{1}{6(1 + \lambda)} \right) V' \left( \partial_i S \right)^2 + \phi(S) \right]. \tag{21}
\]
where \( \phi(S) \) is given by Equation (19), and \( \frac{\partial \Phi(S)}{\partial S} \) is the derivative of function. The TDGL Equation (20) has two steady-state solutions except for a trivial solution \( S = 0 \). One is the uniform solution

\[
S(x, t) = \pm \left[ \frac{6\lambda'' \left( 3 + \lambda \right) \tau V'' - (1 + \lambda)^2}{(1 + \lambda)^2 V''} \right]^{\frac{1}{2}}
\]

(22)

and the other is the kink solution

\[
S(x, t) = \pm \left[ \frac{6\lambda'' \left( 3 + \lambda \right) \tau V'' - (1 + \lambda)^2}{(1 + \lambda)^2 V''} \right]^{\frac{1}{2}} \times \tanh \left[ 3x \left( -\frac{(3 + \lambda)}{(1 + \lambda)^2} + 1 \right) \right] \times (x_i - x_0).
\]

(23)

where \( x_0 \) is a constant. Equation (23) represents the coexisting phase.

By the condition

\[
\frac{\partial \phi}{\partial S} = 0, \quad \frac{\partial^2 \phi}{\partial S^2} > 0.
\]

(24)

Hence, substituting Equation (19) into Equation (24), we can obtain the coexisting curve related to the original parameters

\[
(\Delta x)_{co} = h \pm \left[ \frac{6\lambda'' \left( 3 + \lambda \right) \tau V'' - (1 + \lambda)^2}{(1 + \lambda)^2 V''} \right]^{\frac{1}{2}}
\]

(25)

The spinodal line is given by the following condition

\[
\frac{\partial^2 \phi}{\partial S^2} = 0.
\]

(26)

From Equation (18), we obtain the spinodal line described by the following equation

\[
(\Delta x)_{sp} = h \pm \left[ \frac{2\lambda'' \left( 3 + \lambda \right) \tau V'' - (1 + \lambda)^2}{(1 + \lambda)^2 V''} \right]^{\frac{1}{2}}
\]

(27)

The critical point is given by the condition

\[
\frac{\partial \phi}{\partial S} = 0, \quad \frac{\partial^2 \phi}{\partial S^2} = 0.
\]

(28)

Substituting Equation (19) into Equation (28), we have the critical point related to the original parameters as follows:

\[
(\Delta x)_c = h_c, \quad \tau_c = \frac{(1 + \lambda)^2}{(3 + \lambda) V''}.
\]

(29)

### 5. mKdV Equation and Its Connection to TDGL

In this section, based on the stability condition (11) in Section 3, we use the reductive perturbation method to derive the mKdV equation for the model (4) in
the unstable region of traffic flow. Similar to the derivation of the TDGL equation in Section 4, we study the slowly varying behavior at long wavelengths near the critical point. We also give slow scales for space variable \( n \) and time variable \( t \).

By inserting \( \tau_c = \frac{(1 + \lambda)^3}{(3 + \lambda) V''(h)} \) and \( \tau = (1 + \varepsilon^2) \tau_c \) into Equation (15), making \( b = V'(h) / (1 + \lambda) \), and near the critical point, we obtain:

\[
\varepsilon^4 \left[ \partial_x^2 R - k_1 \partial_x^2 R + k_2 \partial_x^4 R^3 \right] + \varepsilon^5 \left[ k_3 \partial_x^2 R + k_4 \partial_x^4 R + k_5 \partial_x^4 R^3 \right] = 0, \tag{30}
\]

Here, the coefficients \( k_i \) are given in Table 3.

In Table 3, \( V' = dV / d\Delta \bigg|_{\Delta_n = h} \), \( V'' = d^2V / d\Delta^2 \bigg|_{\Delta_n = h} \). We make the following transformation to Equation (30):

\[
T = \frac{1}{k_1} T', \quad R = \frac{k_1}{k_2} R', \tag{31}
\]

so the standard mKdV equation as follows:

\[
\partial_x R = \partial_x^3 R' - \partial_x^3 R^3 - \varepsilon \left[ \frac{k_3}{k_1} \partial_x^2 R' + \frac{k_4}{k_1} \partial_x^4 R' + \frac{k_5}{k_2} \partial_x^4 R^3 \right]. \tag{32}
\]

If we ignore the term of \( O(\varepsilon) \), Equation (32) is the modified KdV equation. Its kink solution is given as

\[
R_c(X, T') = \sqrt{c} \tanh \left( \frac{c}{\sqrt{2}} (X - c T') \right). \tag{33}
\]

Now, assuming that \( R'(X, T') = R_c(X, T') + O(\varepsilon R'(X, T')) \), we take into account the \( O(\varepsilon) \) correction. For the purpose of determining the selected value of the velocity \( c \) for the kink solution, it is necessary to satisfy the solvability condition as \( \left( R_c, M[R_c] \right) = \int_{-\infty}^{\infty} dx R_c M[R_c] \), where \( M[R_c] = \frac{k_3}{k_1} \partial_x^2 R' + \frac{k_4}{k_1} \partial_x^4 R' + \frac{k_5}{k_2} \partial_x^4 R^3 \).

We get the general velocity \( c \) [28],

\[
c = \frac{5k_2k_3}{2k_2k_4 - 3k_1k_5}. \tag{34}
\]

Therefore, the general kink-antikink soliton solution is obtained as follows:

\[
\Delta \left( t \right) = h_c \pm \frac{\sqrt{k_2k_4} \left( \frac{r}{\tau_c} - 1 \right) \tanh \left( \frac{c}{\sqrt{2}} \left( \frac{r}{\tau_c} - 1 \right) \right)}{\tau \left[ 1 - c k_1 \left( \frac{r}{\tau_c} - 1 \right) \right]} t. \tag{35}
\]

Table 3. The coefficients \( k_i \) of (30).

<table>
<thead>
<tr>
<th>( k_1 )</th>
<th>( k_2 )</th>
<th>( k_3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{1}{6(1 + \lambda)} V'' - \frac{(7 + \lambda) r^2}{6(1 + \lambda)} (V'')^2 )</td>
<td>( -\frac{V''}{6(1 + \lambda)} )</td>
<td>( \frac{1}{2(1 + \lambda)} V'' )</td>
</tr>
</tbody>
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<table>
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<tr>
<th>( k_4 )</th>
<th>( k_5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{(15 + \lambda) r^2 (V'')'}{24(1 + \lambda)} (V'')' - \frac{1}{24(1 + \lambda)} V''' )</td>
<td>( \frac{V'' (3 + \lambda) r}{12(1 + \lambda)} V'' - \frac{1}{1 + \lambda} )</td>
</tr>
</tbody>
</table>

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Since the kink soliton solution represents the coexisting phase in the space \((h,a)\), and the kink solution (35) is agreed with the solution (23) obtained from the TDGL Equation (20). We see that the jamming transition can be described by both the TDGL equation with a nontravelling solution and the mKdV equation with a propagating solution [29].

6. Conclusion

We propose an extended optimal velocity model (2) by considering the speed limit with intelligent prompts. Using the linear stability theory, the neutral stability line and the critical point of the new model are derived. The stable condition (11) shows that the effect of intelligent prompt limiting speed has a positive effect on expanding the stable area of traffic flow and easing traffic congestion. In addition, the TDGL equation is derived to describe the traffic behavior near the model critical point by using the reduced perturbation method, and the corresponding two steady-state solutions are obtained. From the TDGL, the spinor line and the critical point equation are calculated. At the same time, we derive the mKdV equation in the unstable region and obtain the relation between TDGL and mKdV equation.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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