

Article

A Microscopic Traffic Model Incorporating Vehicle Vibrations Due to Pavement Condition

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Abstract: A microscopic traffic flow model is developed that incorporates vehicle vibrations due to pavement condition. The Intelligent Driver (ID) model employs a fixed exponent so traffic behavior is the same regardless of the road condition. Thus, it ignores the underlying physics. To address this limitation, the proposed model employs the Pavement Condition Index (PCI) in describing traffic behavior. The performance of both models is evaluated on a 3000 m circular road using the Euler numerical discretization technique. The results show that the performance of the proposed model varies with the pavement condition (PCI), as expected. Furthermore, the traffic flow increases with vehicle speed. The oscillations in speed and density with the proposed model decrease as the PCI increases, and are larger when the speed is higher. Consequently, the results with the proposed model align more closely with reality as they are based on the PCI, and so are a more accurate representation of traffic behavior.

Keywords: traffic exponent; Intelligent Driver model; microscopic traffic flow; Pavement Condition Index; vehicle vibration

MSC: 37M05



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1. Introduction

Pavement condition significantly impacts traffic behavior. Pavement deterioration causes traffic accidents, congestion, pollution, and time delays [1]. Moreover, poor roads impact the smooth flow of traffic, resulting in rider discomfort and increased vehicle operating costs [2]. Congestion lowers vehicle speeds so emissions are increased [1]. Further, vehicle speed is reduced by an average of 55% when the road condition is poor compared to when it is excellent, and average emissions increase by 2.49%. Road safety is a primary concern worldwide as road accidents cause 1.3 million fatalities each year [3]. It is also dangerous as uneven pavement and potholes, damaged concrete, cracks, and exposed rebar can cause drivers to lose control, resulting in severe accidents [4]. Efficient traffic forecasting and control are essential to alleviate traffic problems such as congestion and improve road infrastructure [5]. This requires a practical model for traffic prediction.

Traffic models are typically microscopic or macroscopic, and mesoscopic. Macroscopic models focus on speed and density to describe traffic flow [6], while microscopic models focus on individual vehicles and drivers [7]. They incorporate speed, position, and distance and time headway [8,9].

Gazis, Herman, and Rothery proposed a microscopic model commonly known as the GHR model [10]. This model characterizes driver response considering the speed and distance of leading vehicles. However, driver behavior in changing conditions is

ignored as speed adjustments are based on a constant and not traffic physics. Newell [11] characterized vehicle behavior in dense traffic and showed that velocity (speed) is impacted by the distance headway. An increase in this headway results in higher speeds and lower density. However, high speeds can produce large acceleration, which is neither safe nor realistic.

Wiedemann [12] and Fritzsche [13] developed similar models based on driver behavior under varying conditions. Their results are employed in the PTV VISSIM and PARAMICS simulators, respectively [14]. However, the traffic states have different equations so their models are complex. Wiedemann [15] created an improved model using simulation results for traffic on motorways. However, this model is not stable for a large number of vehicles [16].

An improvement to the Newell model was given in [17], but it neglects speed differences, resulting in acceleration which is very high. Moreover, driver behavior is based on a constant and so traffic physics is ignored. It was shown in [18] that speed differences can be used to accurately characterize speed and time headway in dense traffic. However, average and slow driver behavior are not considered so the results only pertain to aggressive drivers. The model in [19] is widely used because it produces realistic traffic behavior. As a consequence, it is employed in the AIMSUN simulator [14]. However, this model cannot differentiate between acceleration and deceleration and is limited to a small range of parameters [20].

The Intelligent Driver (ID) model was developed in [20] based on driver reaction. This model considers desired velocity (speed) and distance headway to characterize driver behavior [21–23]. Unlike the Gipps model, the ID model provides realistic acceleration and deceleration [14]. As a consequence, it is widely utilized in Adaptive Cruise Control (ACC) and cooperative ACC [24–26]. The ID model is also employed in Simulation of Urban MObility (SUMO) and PTV VISSIM [27]. However, it uses a fixed exponent to characterize traffic. This means that driver behavior is not based on traffic conditions. This is unrealistic as real-world traffic dynamics are influenced by various factors including pavement condition, and this affects driver behavior.

This study introduces a microscopic traffic model that incorporates the pavement condition to accurately represent traffic behavior. The pavement condition is evaluated using the Pavement Condition Index (PCI), which is an indicator of pavement condition and quality, and thus affects driver behavior and traffic flow. It ranges between 0 and 100 [2]. Incorporating the PCI results in a model that provides a more comprehensive and accurate representation of traffic behavior. A flowchart of the methodology employed in this research is given in Figure 1. First, field experiments to determine the impact of vehicle vibrations on the PCI were conducted on the Grand Trunk highway in Peshawar, located in the Khyber Pakhtunkhwa province of Pakistan. This road section spans 7 km and extends from the Chamkani Bus Rapid Transit (BRT) station to Pabbi. Then, the proposed and ID models are implemented using the Euler technique in MATLAB. The results obtained indicate that the proposed model is more suitable for evaluating traffic behavior.



Figure 1. Flowchart of the methodology.

The rest of this paper is organized as follows. In Section 2, traffic flow models are introduced and their stability is analyzed in Section 3. Section 4 outlines the Euler technique and the performance is evaluated in Section 5. The results of this paper are summarized in Section 6.

2. Traffic Models

The ID model is used for microscopic traffic characterization and incorporates factors such as the desired speed v_d , distance to align with leading conditions s , and the difference in speed Δv with the leading vehicle [20]. Driver response is a function of the ratio of average speed v to desired speed v_d , and is expressed as [20]

$$\frac{dv}{dt} = a \left(1 - \left(\frac{v}{v_d} \right)^\delta - \left(\frac{H}{s} \right)^2 \right) \quad (1)$$

where a is the maximum acceleration and δ is a fixed acceleration exponent. H is the desired distance headway during traffic alignment to leading conditions and is given by [20]

$$H = J + Tv + \frac{v\Delta v}{2\sqrt{ad}} \quad (2)$$

where d is the deceleration or minimum acceleration, J is the jam spacing as illustrated in Figure 2, and T is the time required by a vehicle to adjust its speed to the speed of the leading vehicle [5]. H indicates driver desire to maintain a safe distance from the leading vehicle. This is crucial for ensuring safety on the road and preventing collisions. The ID model employs (1) and (2) for traffic by incorporating driver response and distance headway for the alignment of traffic [5].

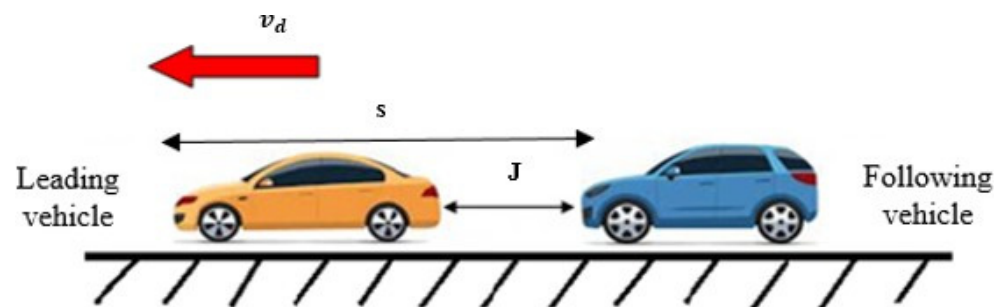


Figure 2. Intelligent Driver (ID) model parameters.

The ID model characterizes driver response to traffic conditions based on a fixed value δ . Thus, driver behavior does not vary based on these conditions, so it is unrelated to traffic physics and results in inadequate and unrealistic traffic characterization.

An acceleration exponent based on the PCI is proposed for the realistic characterization of traffic. Then, δ is a function of vehicle vibrations which are mechanical oscillations. These vibrations are largely generated by the interaction between the road surface and tires, and thus are a major contributor to passenger fatigue and discomfort.

Field experiments were conducted by driving a test vehicle over the road segment in Peshawar, Pakistan, between 12 AM and 2 AM. One lane in each direction was traversed 12 times with speeds of 35 km/h (9.72 m/s), 45 km/h (12.50 m/s), and 55 km/h (15.27 m/s). Thus, for a given speed, a lane was traversed four times. These speeds were selected to represent typical traffic observed on the road segment. Data were collected using an On-Board Diagnostic-II scanner connected to a smartphone with the BotlnckDectr [28] mobile app. This allowed for the recording of various parameters including GPS location, in-vehicle noise, vibration, and time [28]. During the experiments, the smartphone was positioned on the vehicle dashboard. The data were transmitted to the Amazon Web

Services (AWS) cloud. It was then analyzed to obtain the *PCI* of the road segment. The relationships between *PCI* and vehicle vibrations obtained are

$$\delta = -0.0169PCI + 4.068 \quad (3)$$

$$\delta = -0.0265PCI + 5.037 \quad (4)$$

$$\delta = -0.0251PCI + 5.209 \quad (5)$$

for speeds of approximately 9.72 m/s, 12.50 m/s, and 15.27 m/s, respectively. The *PCI* ranges from 0 to 100 where 0 corresponds to a poor road condition and 100 to an excellent road condition. Thus, δ and *PCI* are linearly related. As the pavement condition degrades, the oscillations increase, which reduces passenger comfort, i.e., a higher *PCI* corresponds to lower vibrations. Substituting (3), (4) and (5) in (1) gives the proposed model for speeds of 9.72 m/s, 12.50 m/s, and 15.27 m/s, respectively

$$\frac{dv}{dt} = a \left(1 - \left(\frac{v}{v_d} \right)^{(-0.0169PCI+4.068)} - \left(\frac{H}{s} \right)^2 \right) (v_d = 9.72 \text{ m/s}) \quad (6)$$

$$\frac{dv}{dt} = a \left(1 - \left(\frac{v}{v_d} \right)^{(-0.0265PCI+5.037)} - \left(\frac{H}{s} \right)^2 \right) (v_d = 12.50 \text{ m/s}) \quad (7)$$

$$\frac{dv}{dt} = a \left(1 - \left(\frac{v}{v_d} \right)^{(-0.0251PCI+5.209)} - \left(\frac{H}{s} \right)^2 \right) (v_d = 15.27 \text{ m/s}) \quad (8)$$

An excellent road condition is required to avoid traffic congestion and accidents and efficiently align to forward vehicles. In this case, there is free flow traffic which corresponds to *PCI* = 100. A poor road condition can result in congestion due to the reduction in vehicle speed. In this case, *PCI* = 0 and vehicle acceleration and deceleration are large so the emissions are high. With the proposed model, alignment is according to the *PCI* and is more realistic compared with fixed δ .

The traffic density can be expressed as $D = 1/s_e$ [29] where s_e is the distance headway at equilibrium. In this case, $\Delta v = 0$ so substituting (2) in (1) gives for the ID model

$$a \left(1 - \left(\frac{v}{v_d} \right)^\delta - \left(\frac{J + Tv}{s_e} \right)^2 \right) = 0 \quad (9)$$

and rearranging we obtain

$$s_e = (J + Tv) \left(1 - \left(\frac{v}{v_d} \right)^\delta \right)^{-\frac{1}{2}} \quad (10)$$

Thus, the fixed δ in the ID model results in a constant distance headway between vehicles at equilibrium regardless of the traffic conditions. In contrast, in the proposed model the distance headway is based on the *PCI*. The distance headway at equilibrium is obtained by substituting (3), (4), and (5) in (10) which gives

$$s_e = (J + Tv) \left(1 - \left(\frac{v}{v_d} \right)^{(-0.0169PCI+4.068)} \right)^{-\frac{1}{2}} (v_d = 9.72 \text{ m/s}) \quad (11)$$

$$s_e = (J + Tv) \left(1 - \left(\frac{v}{v_d} \right)^{(-0.0265PCI+5.037)} \right)^{-\frac{1}{2}} (v_d = 12.50 \text{ m/s}) \quad (12)$$

$$s_e = (J + Tv) \left(1 - \left(\frac{v}{v_d} \right)^{(-0.0251PCI+5.209)} \right)^{-\frac{1}{2}} \quad (v_d = 15.27 \text{ m/s}) \quad (13)$$

The product of density and speed is traffic flow [8,30] so that

$$F = \frac{v}{s_e} \quad (14)$$

and substituting (10) in (14) gives the flow for the ID model as

$$F = \frac{v}{(J + Tv) \left(1 - \left(\frac{v}{v_d} \right)^{\delta} \right)^{-\frac{1}{2}}} \quad (15)$$

This is unrealistic as it relies on a fixed exponent. The proposed model considers the PCI to determine traffic flow and so is more realistic. The traffic flow can be expressed as

$$F = \frac{v}{(J + Tv) \left(1 - \left(\frac{v}{v_d} \right)^{(-0.0169PCI+4.068)} \right)^{-\frac{1}{2}}} \quad (v_d = 9.72 \text{ m/s}) \quad (16)$$

$$F = \frac{v}{(J + Tv) \left(1 - \left(\frac{v}{v_d} \right)^{(-0.0265PCI+5.037)} \right)^{-\frac{1}{2}}} \quad (v_d = 12.50 \text{ m/s}) \quad (17)$$

$$F = \frac{v}{(J + Tv) \left(1 - \left(\frac{v}{v_d} \right)^{(-0.0251PCI+5.209)} \right)^{-\frac{1}{2}}} \quad (v_d = 15.27 \text{ m/s}) \quad (18)$$

The proposed model indicates that when the road condition is poor, the vehicle vibrations are large and the flow is small, whereas when the road condition is excellent, the vehicle vibrations are small and the flow is large. Further, the proposed model can predict traffic behavior in real-time to help ACC systems better anticipate and adapt to changes in traffic conditions. An ACC system guided by the proposed model can adjust the vehicle speed and following distance in response to the observed traffic density. When the density is high, the ACC can reduce the speed and maintain a safe distance to ensure safety and a smooth traffic flow. Conversely, when the density is low, the ACC can increase the speed while maintaining a safe distance to improve efficiency.

3. Stability Analysis

This section presents an analysis of the stability of traffic models considering an infinitely long road. Identical vehicles are assumed with a constant equilibrium distance headway [31]. Therefore, drivers adjust to forward conditions with minimal acceleration, so there are only small changes in the equilibrium velocity v_e associated with s_e . The corresponding change in distance headway, denoted by a , is also small as is the change in velocity denoted by b . The distance headway can then be expressed as

$$s = s_e + a, \quad (19)$$

and

$$v = v_e(s_e) + b. \quad (20)$$

The temporal change in velocity during traffic alignment over the distance headway is [32]

$$a(t) = \frac{da}{dt} = b_l - b_F, \quad (21)$$

where the subscripts F and l denote the following and leading vehicles, respectively. Given the minor variations in $v_e(s_e)$, the adjustments in headway are negligible. Consequently, $b(t)$ during alignment can be expressed as [31]

$$b(t) = \frac{db}{dt} = f_s a_F + (f_v + f_{\Delta v}) b_F - f_{\Delta v} b_l, \quad (22)$$

where f_v , $f_{\Delta v}$, and f_s denote the partial derivatives w.r.t. velocity, change in velocity, and distance headway, respectively, which are

$$f_v = \frac{\partial f}{\partial v}, \quad f_{\Delta v} = \frac{\partial f}{\partial \Delta v} \quad \text{and} \quad f_s = \frac{\partial f}{\partial s}.$$

Using Fourier–Ansatz to express (21) and (22) gives

$$a(t) = \hat{a} e^{\gamma t + ik}, \quad (23)$$

$$b(t) = \hat{b} e^{\gamma t + ik}, \quad (24)$$

so (23) and (24) can be written as

$$\begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = \begin{pmatrix} \hat{a} \\ \hat{b} \end{pmatrix} e^{\gamma t + ik}, \quad (25)$$

where $\gamma = \alpha + i\omega$ corresponds to the traffic oscillations during alignment and $i = \sqrt{-1}$. The real part α corresponds to the amplitude change and $\omega = \frac{2\pi}{T}$ is the oscillation frequency with oscillation period T . The parameter k denotes driver delay [31], while $\hat{a}$ and $\hat{b}$ are the changes in velocity and distance headway, respectively.

Substituting (25) in (21) and (22), gives

$$a(t) = b - b e^{ik}, \quad (26)$$

$$b(t) = f_s a e^{ik} + (f_v + f_{\Delta v}) b e^{ik} - f_{\Delta v} b. \quad (27)$$

Model stability requires that the real components of the eigenvalues are negative. The eigenvalues are the solution of

$$\left| j - \begin{pmatrix} \lambda & 0 \\ 0 & \lambda \end{pmatrix} \right| = 0. \quad (28)$$

The Jacobian matrix is

$$j = \begin{pmatrix} j_{11} & j_{12} \\ j_{21} & j_{22} \end{pmatrix},$$

where j_{11} and j_{21} are the gradients of (26) and (27) w.r.t. a and j_{12} and j_{22} are the gradients of (26) and (27) w.r.t. b . We have

$$j = e^{ik} \begin{pmatrix} 0 & e^{-ik} - 1 \\ f_s & (f_v + f_{\Delta v}) - f_{\Delta v} e^{-ik} \end{pmatrix}. \quad (29)$$

and substituting this in (28) gives

$$\left| \begin{pmatrix} \lambda & 1 - e^{-ik} \\ -f_s & \lambda - f_v - f_{\Delta v} + f_{\Delta v} e^{-ik} \end{pmatrix} \right| = 0, \quad (30)$$

so that

$$\lambda^2 + (-f_v - f_{\Delta v} + f_{\Delta v} e^{-ik}) \lambda + f_s (1 - e^{-ik}) = 0. \quad (31)$$

Setting $M(k) = -f_v - f_{\Delta v} + f_{\Delta v}e^{-ik}$ and $N(k) = f_s(1 - e^{-ik})$, (24) becomes

$$\lambda^2 + M(k)\lambda + N(k) = 0. \quad (32)$$

Thus, the eigenvalues from (32) are

$$\lambda_{1,2} = -\frac{M(k)}{2} \left(1 \pm \sqrt{1 - \frac{4N(k)}{M^2(k)}} \right), \quad (33)$$

A model is string stable [31] if the real components of the eigenvalues are negative. Under this condition, traffic oscillations diminish over time and the flow becomes stable and smooth [33]. Conversely, a model is considered unstable if traffic oscillations increase and are large as in congestion. In this case, acceleration is high unlike when there is string stability [29]. As the model becomes unstable, $k \rightarrow 0$, leading to minimal delay between flow changes (traffic waves) [31].

Approximating $M(k)$ and $N(k)$ using Taylor series for a small delay, i.e., $k \rightarrow 0$, gives

$$M(k) = -f_v - if_{\Delta v}k, \quad (34)$$

$$N(k) = if_s k + \frac{f_s}{2}k^2. \quad (35)$$

From [31], at equilibrium

$$f_s = -v'_e(s_e)f_v. \quad (36)$$

where $v'_e(s_e)$ is the equilibrium speed gradient relative to the distance headway. Then, (35) becomes

$$N(k) = -iv'_e(s_e)f_v - \frac{v'_e(s_e)}{2}f_v. \quad (37)$$

Let

$$\begin{aligned} M(k) &= x_1 + x_2k, \\ N(k) &= y_1k + y_2k^2, \end{aligned} \quad (38)$$

where

$$\begin{aligned} x_1 &= -f_v, \\ x_2 &= -if_{\Delta v}, \\ y_1 &= -iv'_e(s_e)f_v = iv'_e(s_e)x_1, \\ y_2 &= -\frac{v'_e(s_e)}{2}f_v = \frac{v'_e(s_e)}{2}x_1. \end{aligned} \quad (39)$$

Considering a Taylor series expansion, the square root in (33) can be approximated as

$$\sqrt{1 - \frac{4N(k)}{M^2(k)}} = 1 - \frac{2N(k)}{M^2(k)} - \frac{2N^2(k)}{M^4(k)}, \quad (40)$$

which gives

$$\lambda_2 = \frac{-N(k)M^2(k) - N^2(k)}{M^3(k)}. \quad (41)$$

Using (38)

$$\lambda_2 = -\frac{y_1}{x_1}k + \left(\frac{y_1x_2}{x_1^2} - \frac{y_2}{x_1} - \frac{y_1^2}{x_1^3} \right)k^2, \quad (42)$$

and then from (39), we obtain

$$\lambda_2 = -iv'_e(s_e)k + \frac{v'_e(s_e)}{f_v} \left[\frac{-2f_{\Delta v} - f_v}{2} - v'_e(s_e) \right] k^2. \quad (43)$$

The real part of (43) represents the rate at which the traffic oscillation amplitude changes, signifying growth or decay. When this real part is negative, the traffic flow is string-stable, since

$$v'_e(s_e) \geq 0 \text{ and } f_v < 0. \quad (44)$$

Then, $\left[-\frac{2f_{\Delta v}-f_v}{2} - v'_e(s_e)\right]$ is the string stability criterion [27] which can be expressed as

$$v'_e(s_e) \leq -\frac{f_v}{2} - f_{\Delta v}. \quad (45)$$

From (44) and (45), the product of $\left[-\frac{2f_{\Delta v}-f_v}{2} - v'_e(s_e)\right]$ and $\frac{v'_e(s_e)}{f_v}$ indicates that λ_2 has a negative real part. Further, at equilibrium

$$f_v = a \left(-\frac{\delta v_e(s_e)^{\delta-1}}{v_d^\delta} - \frac{2T(J + v_e(s_e)T)}{s_e^2} \right), \quad (46)$$

$$f_{\Delta v} = -\frac{v_e(s_e)}{s_e} \sqrt{\frac{a}{d}} \left(\frac{J + v_e(s_e)T}{s_e} \right). \quad (47)$$

Using (46) and (47), the criterion for string stability from (44) is

$$v'_e(s_e) \leq \frac{a \left(\delta(s_e)^2 v_e(s_e)^{\delta-1} + 2TJv_d^\delta + 2v_e(s_e)T^2v_d^\delta \right)}{2(s_e)^2 v_d^\delta} + \frac{v_e(s_e) \sqrt{ad}(s_e + Tv_e(s_e))}{(s_e)^2 d} \quad (48)$$

Thus, the velocity with the ID model is determined by δ . A higher value improves stability but may lead to optimistic performance in congestion. Consequently, increasing δ for stability reasons ignores traffic physics and can produce unrealistic results [5]. Changes in velocity during traffic alignment are influenced by driver response and thus pavement condition. Hence, more realistic behavior is obtained using (3), (4), and (5) for δ according to the speed. The stability criteria for the proposed model with speeds 9.72 m/s, 12.50 m/s, and 15.27 m/s are then

$$v'_e(s_e) \leq \frac{a \left((-0.0169PCI + 4.068)(s_e)^2 v_e(s_e)^{(-0.0169PCI+4.068)-1} + 2TJv_d^{(-0.0169PCI+4.068)} + 2v_e(s_e)T^2v_d^{(-0.0169PCI+4.068)} \right)}{2(s_e)^2 v_d^{(-0.0169PCI+4.068)}} + \frac{v_e(s_e) \sqrt{ad}(s_e + Tv_e(s_e))}{(s_e)^2 d} \quad (49)$$

$$v'_e(s_e) \leq \frac{a \left((-0.0265PCI + 5.037)(s_e)^2 v_e(s_e)^{(-0.0265PCI+5.037)-1} + 2TJv_d^{(-0.0265PCI+5.037)} + 2v_e(s_e)T^2v_d^{(-0.0265PCI+5.037)} \right)}{2(s_e)^2 v_d^{(-0.0265PCI+5.037)}} + \frac{v_e(s_e) \sqrt{ad}(s_e + Tv_e(s_e))}{(s_e)^2 d} \quad (50)$$

$$v'_e(s_e) \leq \frac{a \left((-0.0251PCI + 5.209)(s_e)^2 v_e(s_e)^{(-0.0251PCI+5.209)-1} + 2TJv_d^{(-0.0251PCI+5.209)} + 2v_e(s_e)T^2v_d^{(-0.0251PCI+5.209)} \right)}{2(s_e)^2 v_d^{(-0.0251PCI+5.209)}} + \frac{v_e(s_e) \sqrt{ad}(s_e + Tv_e(s_e))}{(s_e)^2 d} \quad (51)$$

respectively. When the pavement is in good condition, vehicles can more easily adjust to changes in traffic ensuring string stability. Conversely, pavement in poor condition results in greater adjustments to changes in traffic which may not result in a smooth flow.

4. The Euler Technique

The Euler technique is used to evaluate the proposed and ID models. It is a simple but effective method to solve systems of differential equations and is widely used in traffic simulators such as SUMO [34] and AIMSUN [35]. This technique divides time into discrete steps and the vehicle position, speed, and acceleration are approximated using the model at each time step. The change in distance w.r.t. time results in a change in speed given by

$$\frac{ds}{dt} = v, \quad (52)$$

and temporal changes in speed lead to changes in acceleration. Denote the right-hand side of (1), (6), (7), and (8) by Y , then

$$\frac{dv}{dt} = Y. \quad (53)$$

For the Euler technique, the position and speed for the ID and proposed models is

$$s_f^{x+1} = s_f^x + \Delta t \times v_f^x \quad (54)$$

$$v_f^{x+1} = v_f^x + \Delta t \times Y_f^x \quad (55)$$

where x is the current time step and $x + 1$ is the next time step. s_f^x , v_f^x , and Y_f^x are the position, speed, and acceleration, respectively, of the following vehicle in the x th time interval where

$$t = x\Delta t \quad (56)$$

and Δt is the duration of a time step.

5. Performance Evaluation

In this section, the performance of the proposed model and ID models is evaluated on a circular road of length 3000 m. The Euler scheme is employed with time step $\Delta t = 0.50$ s. The proposed model is simulated for 400 s and the ID model for 150 s. Based on (3), (4), and (5) the desired speed v_d for the proposed model is set to 9.72 m/s, 12.50 m/s, and 15.27 m/s. The desired speed for the ID model is 20 m/s [22]. The jam spacing is set to 2.0 m [31], the maximum acceleration is 0.73 m/s², and the minimum acceleration is 1.67 m/s² [20]. The acceleration exponent δ is typically 1 or greater and is often set to 4 [20]. Thus, here $\delta = 1, 4$ and 20. The PCI values considered are $PCI = 0, 50$ and 100. The maximum normalized density is set to $1/J = 0.50$ and the critical density is 0.25 [36]. The maximum flow is obtained at the critical density with speed v_d . Thus, the speed is normalized by v_d and the flow is normalized by $0.25 \times v_d$. The simulation parameters are summarized in Table 1.

Table 1. Simulation Parameters.

Parameter	Values
Desired speed for the proposed model, v_d	9.72 m/s, 12.50 m/s and 15.27 m/s
Desired speed for the ID model, v_d	20 m/s
Time headway for ID and proposed models, T	2.0 s
Critical density	0.25
Jam spacing, J	2.0 m
Maximum density	$1/J = 0.50$
Maximum acceleration, a	0.73 m/s ²
Vehicle length, L	5.0 m
Acceleration exponent for the ID model, δ	1, 4 and 20
Pavement Condition Index, PCI	0, 50 and 100
Minimum acceleration, d	1.67 m/s ²
Time step, Δt	0.50 s

Figure 3 gives the normalized flow for the proposed model with $v_d = 9.72$ and $PCI = 0, 50$, and 100 . When $PCI = 0$, the flow at 19.0 s is 0.0010 . It is 0.0021 at 106.5 s, increasing to 0.0032 at 293.0 s and 0.0035 at 400 s. When $PCI = 50$, the flow at 19.5 s is 0.0010 . It is 0.0020 at 162.5 s, increasing to 0.0031 at 288.0 s and 0.0038 at 400 s. When $PCI = 100$, the flow at 21.5 s is 0.0010 . It is 0.0025 at 172.0 s, increasing to 0.0033 at 285.5 s and 0.0044 at 400 s.

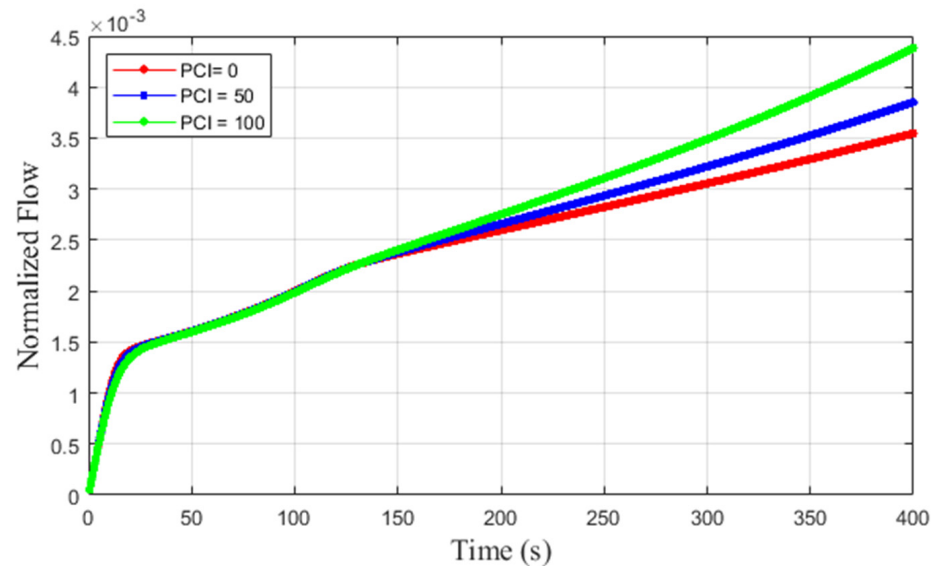


Figure 3. Normalized flow for the proposed model with $v_d = 9.72$ m/s over a 3000 m circular road.

Figure 4 gives the normalized flow for the proposed model with $v_d = 12.50$ m/s and $PCI = 0, 50$, and 100 . When $PCI = 0$, the flow at 20.0 s is 0.0012 . It is 0.0029 at 156.0 s, increasing to 0.0042 at 268.5 s and 0.0054 at 400 s. When $PCI = 50$, the flow at 22.5 s is 0.0013 . It is 0.0033 at 167.0 s, increasing to 0.0045 at 276.0 s and 0.0063 at 400 s. When $PCI = 100$, the flow at 23.5 s is 0.0010 . It is 0.0037 at 179.0 s, increasing to 0.0062 at 313.5 s and 0.0110 at 400 s.

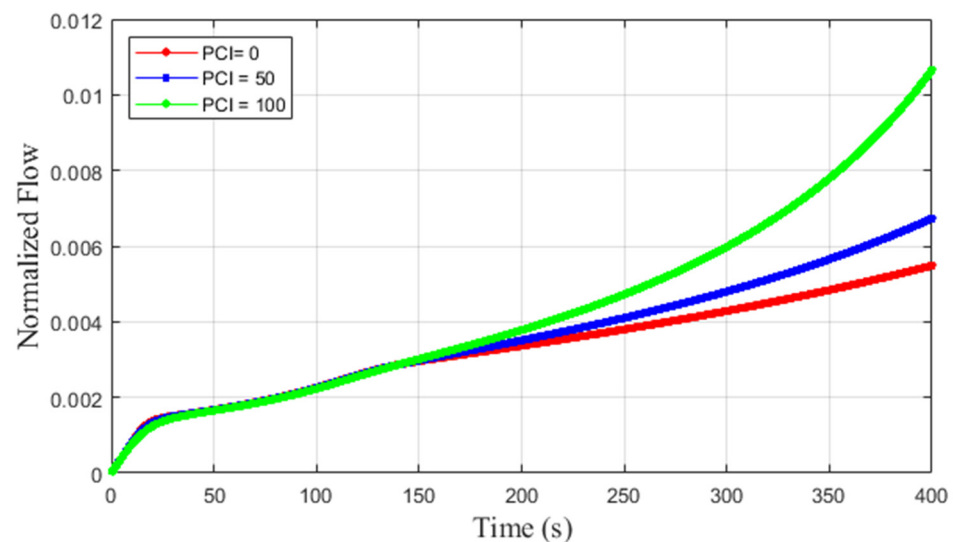


Figure 4. Normalized flow for the proposed model with $v_d = 12.50$ m/s over a 3000 m circular road.

Figure 5 gives the normalized flow for the proposed model with $v_d = 15.27$ m/s and $PCI = 0, 50$, and 100 . When $PCI = 0$, the flow at 22.0 s is 0.0013 . It is 0.0050 at 217.5 s, increasing to 0.0079 at 307.5 s and 0.0140 at 400 s. When $PCI = 50$, the flow at 25.0 s is

0.0013. It is 0.0052 at 220.5 s, increasing to 0.0110 at 324.0 s and 0.0270 at 400 s. When $PCI = 100$, the flow at 27.5 s is 0.0010, increasing to 0.0070 at 234.5 s and 0.0770 at 400 s.

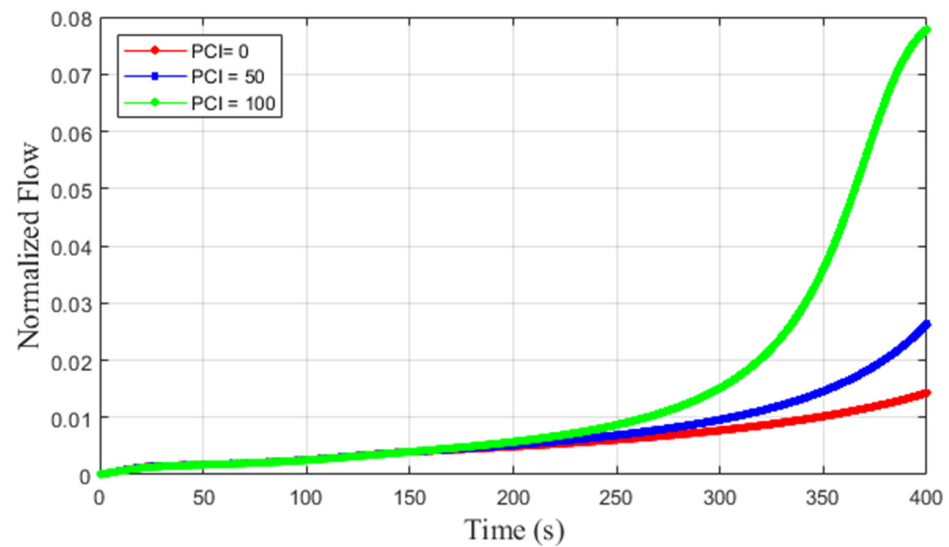


Figure 5. Normalized flow for the proposed model with $v_d = 15.27$ m/s over a 3000 m circular road.

Figure 6 gives the normalized flow for the ID model with $\delta = 1, 4$, and 20 and $v_d = 20$ m/s. When $\delta = 1$, the flow at 31.5 s is 0.0013, increasing to 0.0024 at 94.0 s and 0.0063 at 150 s. When $\delta = 4$, the flow at 33.0 s is 0.0017. It is 0.0020 at 80.0 s, increasing to 0.0039 at 116.0 s and 0.0088 at 150 s. When $\delta = 20$, at 28.0 s the flow is 0.0012. It is 0.0032 at 100.5 s, increasing to 0.0060 at 130.0 s and 0.0095 at 150 s.

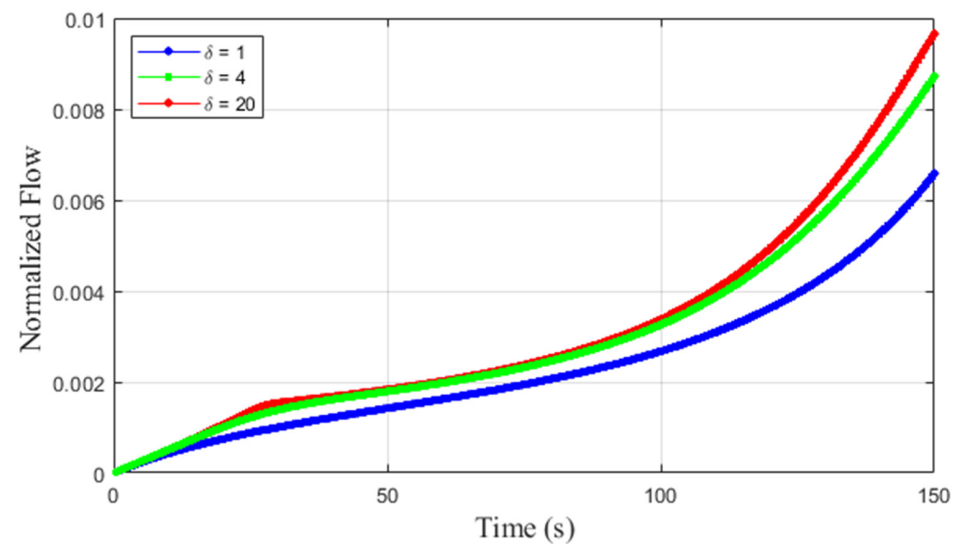


Figure 6. Normalized flow for the ID model with $\delta = 1, 4$, and 20 over a 3000 m circular road.

Figure 7 gives the normalized speed with $v_d = 9.72$ m/s and $PCI = 0, 50$ and 100 for the proposed model. When $PCI = 0$, the speed is 0.39 from 0.5 s to 15.0 s, decreasing to 0.23 at 15.5 s, and then increasing to 0.46 at 20.0 s. The speed oscillates between 0.16 and 0.64 from 236.5 s to 399.0 s as indicated in Figure 7a. The speed when $PCI = 50$ is similar to that when $PCI = 0$. It is 0.39 from 0.5 s to 15.0 s, decreasing to 0.23 at 15.5 s, and then increasing to 0.46 at 21.0 s. The speed oscillates between 0.21 and 0.58 from 263.0 s to 399.5 s as indicated in Figure 7b. When $PCI = 100$, the speed is 0.40 from 0.5 s to 15.0 s, decreasing to 0.23 at 15.5 s, and then increasing to 0.46 at 19.5 s. The speed oscillates between 0.32 and 0.48 from 315.0 s to 399.0 s as indicated in Figure 7c. For all PCI values, there are road

segments where the speed is constant such as between -1947.8 m and -426.7 m at 397.5 s when $PCI = 0$, between -1932.3 m and -228.4 m at 392.0 s when $PCI = 50$, and between -1962.4 m and -428.1 m at 393.5 s when $PCI = 100$.

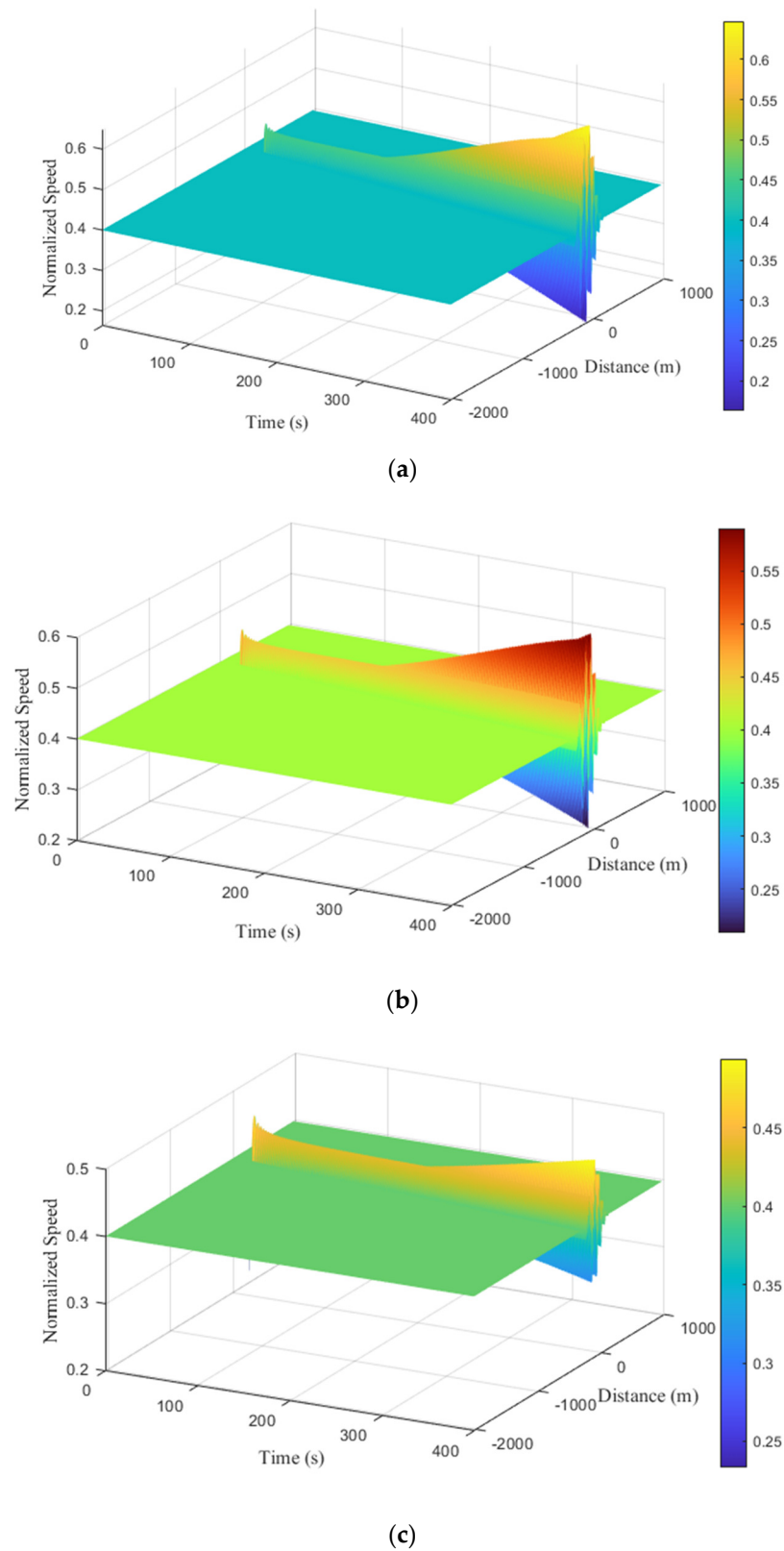


Figure 7. Normalized speed for the proposed model with $v_d = 9.72$ m/s over a 3000 m circular road: (a) $PCI = 0$; (b) $PCI = 50$; (c) $PCI = 100$.

Figure 8 gives the normalized speed with $v_d = 12.50$ m/s and $PCI = 0, 50$, and 100 for the proposed model. When $PCI = 0$, the speed from 0.5 s to 15.0 s is 0.15 , decreasing to 0.09 at 15.5 s, and then increasing to 0.18 at 19.5 s. The speed oscillates between 0.06 and 0.27 from 255.0 s to 399.0 s as indicated in Figure 8a. Similarly, when $PCI = 50$ the speed is 0.15 from 0.5 s to 15.0 s, decreasing to 0.09 at 15.5 s, and then increasing to 0.18 at 20.5 s. The speed oscillates between 0.06 and 0.26 from 258.0 s to 399.0 s as indicated in Figure 8b. The speed is also similar when $PCI = 100$. It is 0.15 from 0.5 s to 15.0 s, decreasing to 0.09 at 15.5 s and then increasing to 0.18 at 19.5 s. The speed oscillates between 0.09 and 0.22 from 294.5 s to 399.5 s as indicated in Figure 8c. For all PCI values, there are road segments where the speed is constant such as between -2022.5 m and -237.5 m at 397.0 s when $PCI = 0$, between -1922.7 m and -245.5 m at 395.0 s when $PCI = 50$, and between -1953.75 m and -230.0 m at 390.0 s when $PCI = 100$.

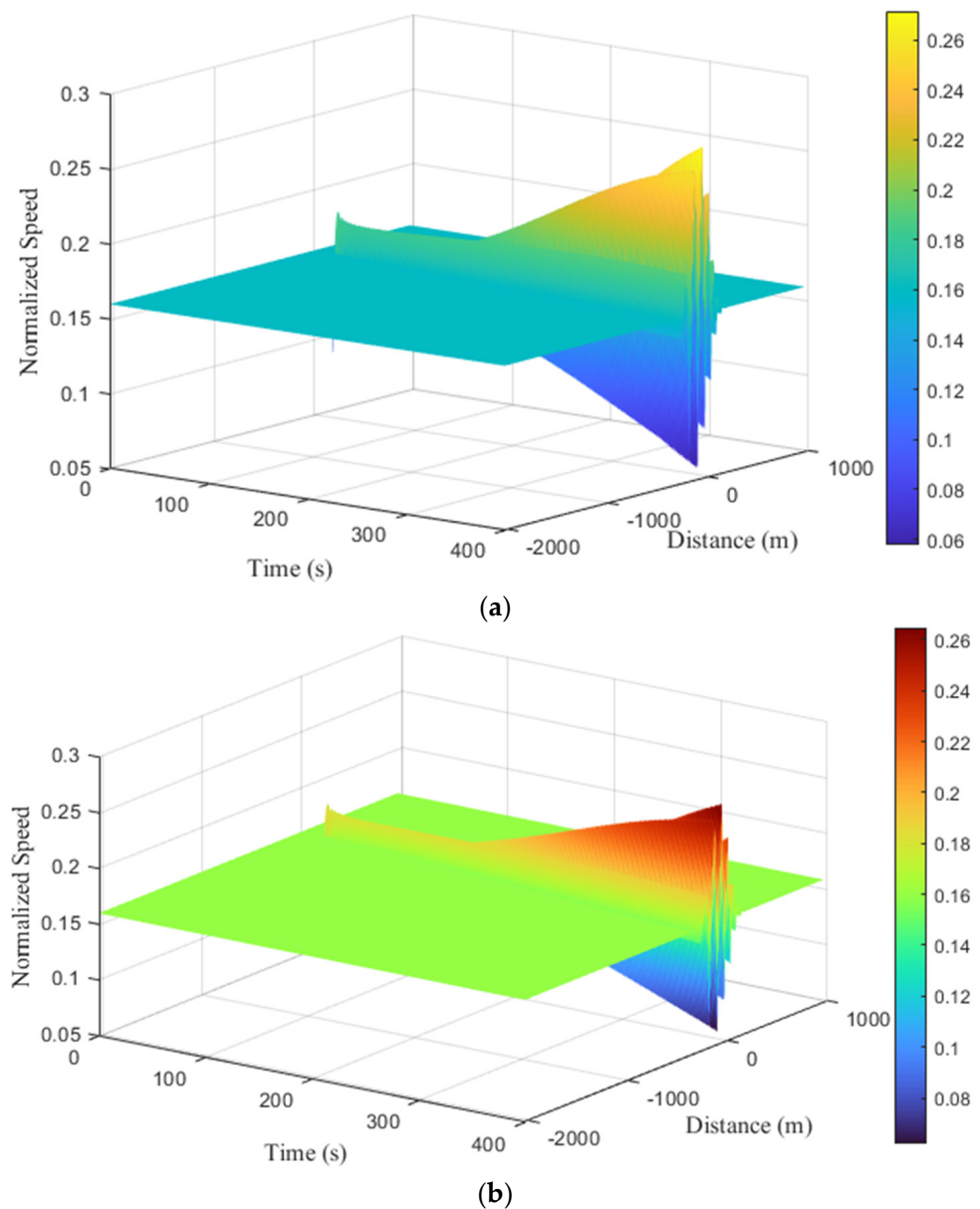


Figure 8. Cont.

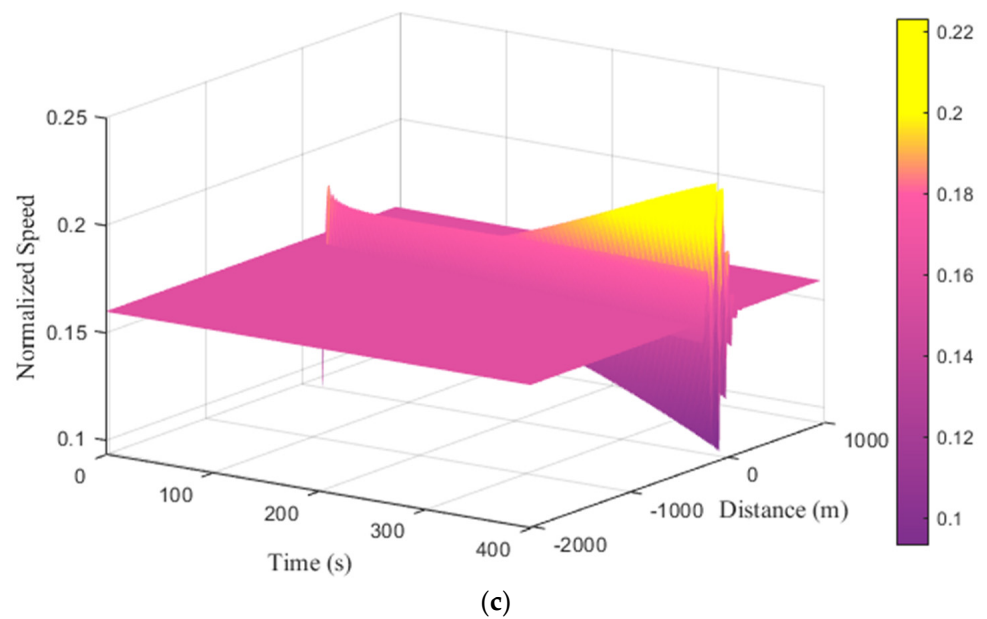


Figure 8. Normalized speed for the proposed model with $v_d = 12.50$ m/s over a 3000 m circular road: (a) $PCI = 0$; (b) $PCI = 50$; (c) $PCI = 100$.

Figure 9 gives the normalized speed with $v_d = 15.27$ m/s and $PCI = 0, 50$, and 100 for the proposed model. When $PCI = 0$, the speed from 0.5 s to 15.0 s is 0.11, decreasing to 0.06 at 15.5 s, and then increasing to 0.13 at 19.5 s. The speed oscillates between 0.04 and 0.20 from 241.0 s to 399.0 s as indicated in Figure 9a. The speed behavior is similar when $PCI = 50$. It is 0.11 from 0.5 s to 15.0 s, decreasing to 0.06 at 15.5 s, and then increasing to 0.14 at 20.5 s. The speed oscillates between 0.04 and 0.20 from 267.5 s to 399.0 s as indicated in Figure 9b. Similar speed behavior also occurs when $PCI = 100$. It is 0.11 from 0.5 s to 15.0 s, decreasing to 0.06 at 15.5 s, and then increasing to 0.13 at 20.5 s. The speed oscillates between 0.05 and 0.18 from 278.5 s to 399.5 s as indicated in Figure 9c. For all PCI values, there are road segments where the speed is constant such as between -1945.4 m and -244.3 m at 391.0 s when $PCI = 0$, between -1911.8 m and -239.7 m at 388.5 s when $PCI = 50$, and between -1817.1 m and -371.4 m at 384.0 s when $PCI = 100$.

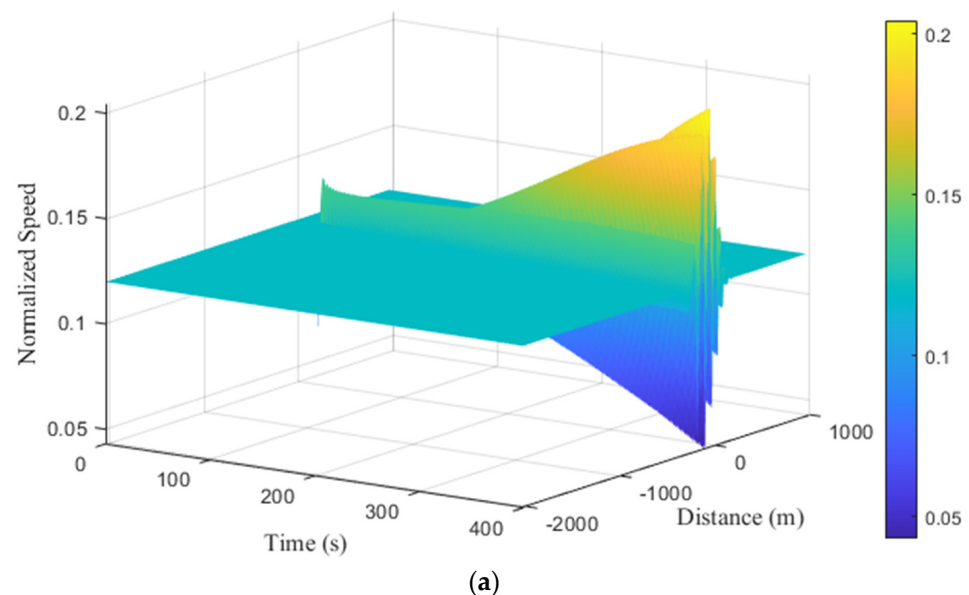


Figure 9. Cont.

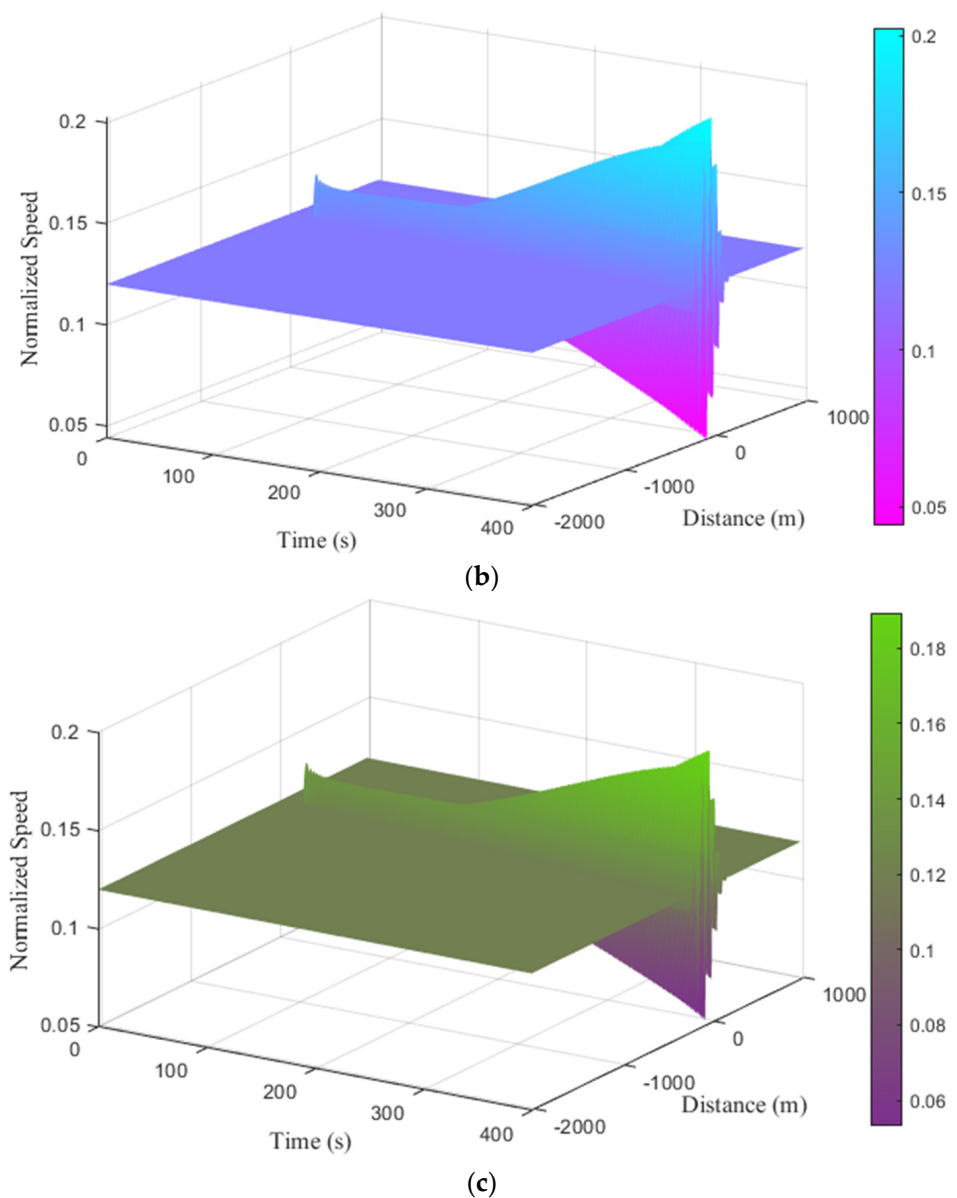


Figure 9. Normalized speed for the proposed model with $v_d = 15.27$ m/s over a 3000 m circular road: (a) $PCI = 0$; (b) $PCI = 50$; (c) $PCI = 100$.

Figure 10 gives the normalized speed for the ID model with $v_d = 15.27$ m/s and $\delta = 1, 4$, and 20. When $\delta = 1$, the speed is 0.10 until 15.0 s. It is 0.05 at 15.5 s and then increases to 0.11 at 21.0 s. The speed oscillates between 0.09 and 0.10 from 118.0 s to 149.5 s as indicated in Figure 10a. When $\delta = 4$, the speed is 0.09 until 15.0 s, decreasing to 0.05 at 15.5 s, and then increasing to 0.11 at 19.5 s. The speed oscillates between 0.08 and 0.11 from 122.5 s to 149.5 s as indicated in Figure 10b. When $\delta = 20$, the speed is 0.1 until 15.0 s, decreasing to 0.05 at 15.5 s, and then increasing to 0.11 at 20.5 s. The speed oscillates between 0.08 and 0.11 from 118.5 s to 150.0 s as indicated in Figure 10c. For all the values of δ , there are road segments where the speed is constant such as between -2590.0 m and -322.0 m at 148.0 s when $\delta = 1$, between -2498.0 m and -292.0 m at 147.0 s when $\delta = 4$, and between -2594.0 m and -374.0 m at 149.0 s when $\delta = 20$.

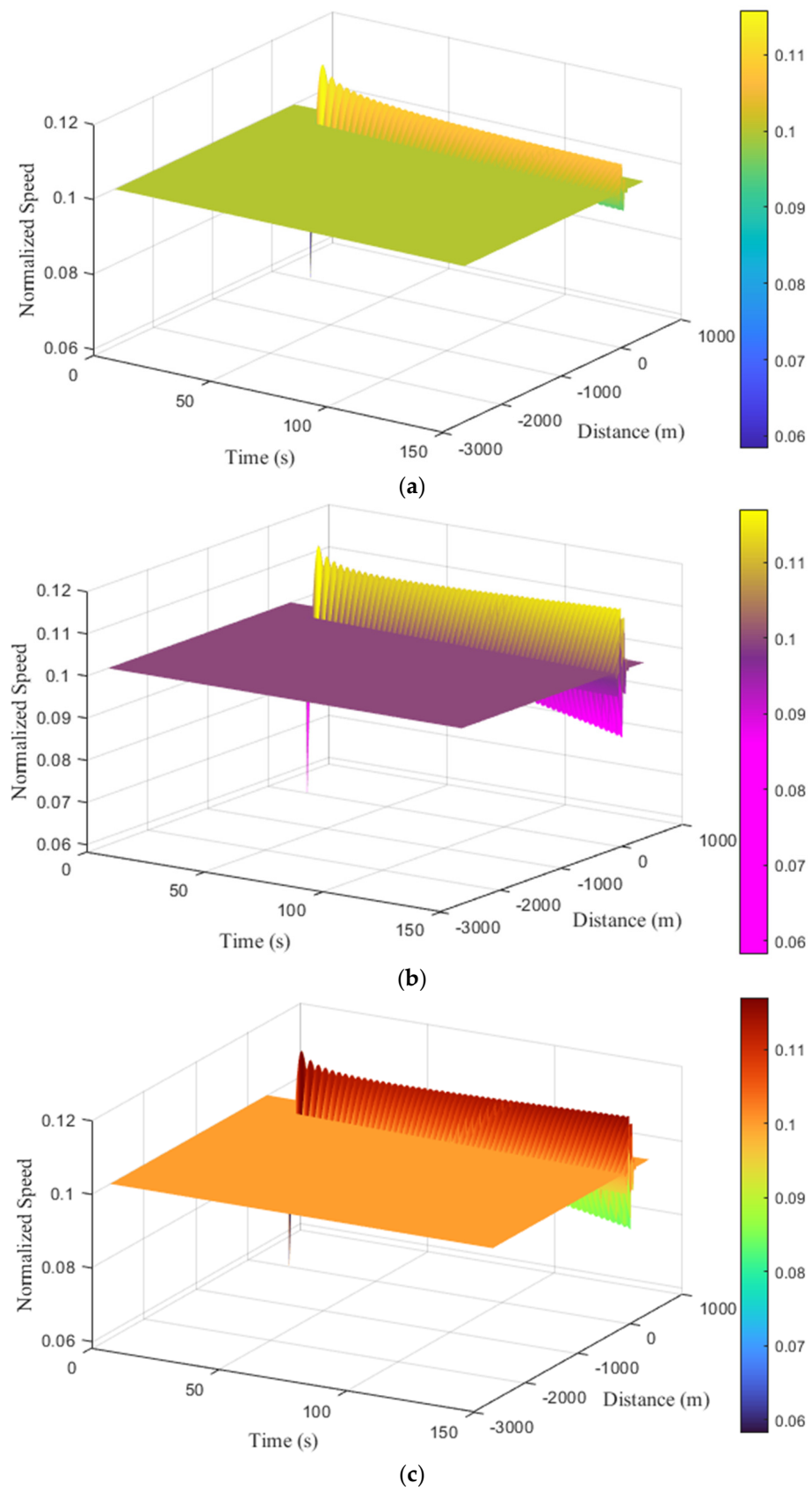


Figure 10. Normalized speed for the ID model over a 3000 m circular road: (a) $\delta = 1$; (b) $\delta = 4$; (c) $\delta = 20$.

Figure 11 gives the normalized density for the proposed model with $v_d = 9.72$ m/s and $PCI = 0, 50$ and 100 . When $PCI = 0$, the density is 0.17 until 31.0 s. It is 0.20 at 32.0 s, decreasing to 0.13 at 32.5 s. The density oscillates between 0.13 and 0.21 from 279.5 s to 398.5 s as indicated in Figure 11a. When $PCI = 50$, the density is 0.16 until 31.0 s. It is 0.20 at 32.0 s, decreasing to 0.13 at 33.0 s. The density oscillates between 0.14 and 0.19 from 277.5 s to 399.5 s, and then it varies between 0.16 and 0.23 as indicated in Figure 11b. When $PCI = 100$, the density is 0.16 until 31.0 s. It is 0.20 at 32.0 s, decreasing to 0.13 at 32.5 s. It oscillates between 0.14 and 0.18 from 313.5 s to 398.5 s, and then varies between 0.16 and 0.18 as indicated in Figure 11c.

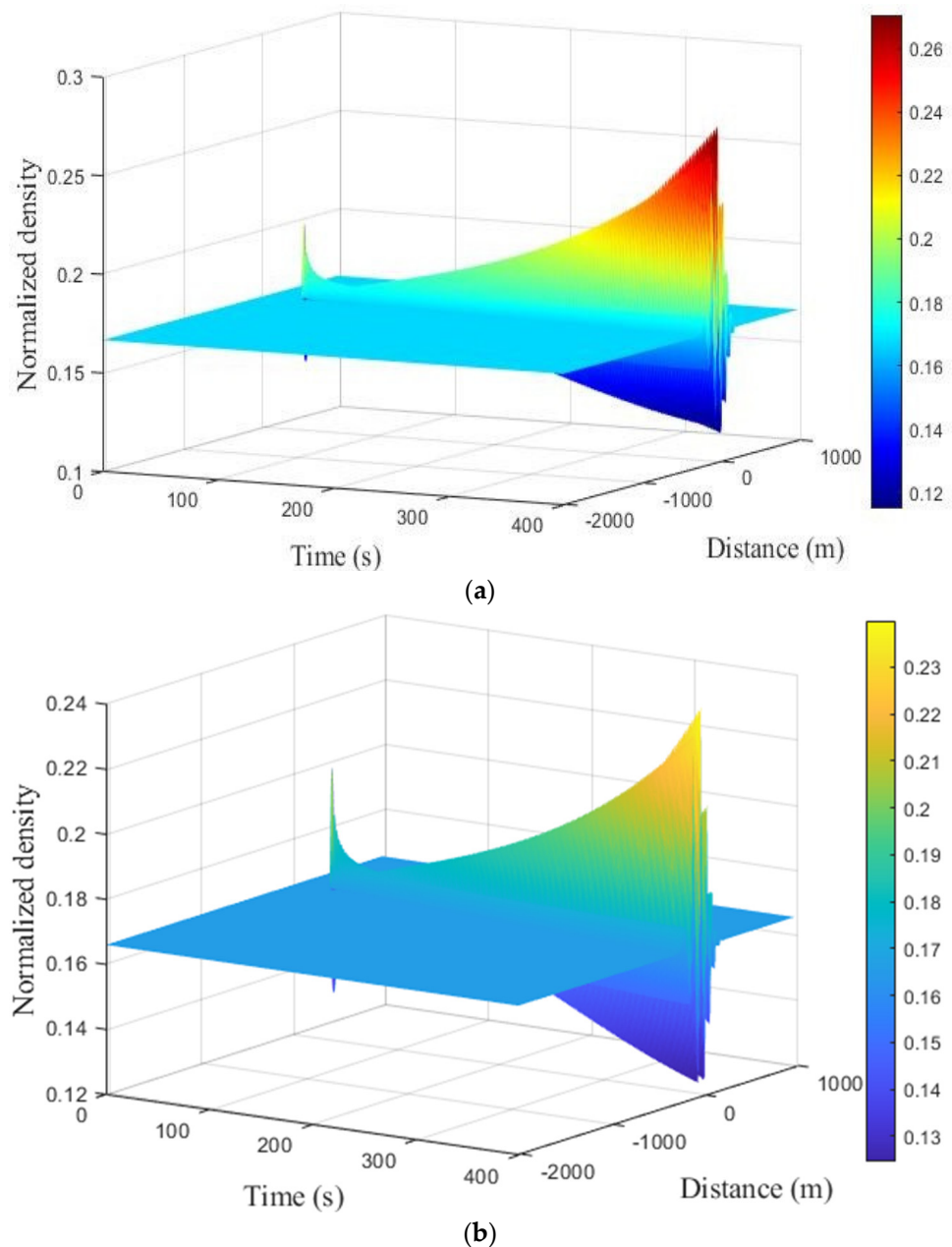


Figure 11. Cont.

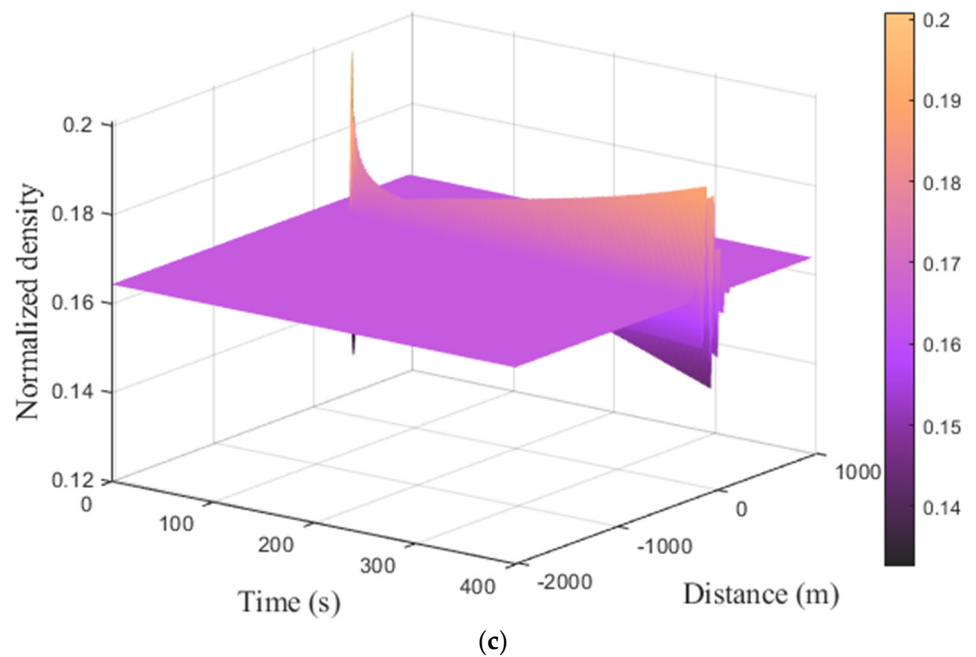


Figure 11. Normalized density for the proposed model with $v_d = 9.72$ m/s over a 3000 m circular road: (a) $PCI = 0$; (b) $PCI = 50$; (c) $PCI = 100$.

Figure 12 gives the normalized density for the proposed model with $v_d = 12.50$ m/s and $PCI = 0, 50$ and 100 . When $PCI = 0$, the density is 0.17 until 31.0 s, increasing to 0.20 at 32.0 s and then decreasing to 0.13 at 32.5 s. The density oscillates between 0.13 and 0.21 from 271.5 s to 398.0 s, and then it varies between 0.17 and 0.28 as indicated in Figure 12a. When $PCI = 50$, the density is 0.17 until 31.0 s, increasing to 0.20 at 32.0 s, and then decreasing to 0.13 at 32.5 s. The density oscillates between 0.13 and 0.23 from 269.0 s to 399.0 s, and then it varies between 0.17 and 0.27 as indicated in Figure 12b. When $PCI = 100$, the density is 0.16 until 31.0 s, increasing to 0.20 at 31.5 s, and then decreasing to 0.13 at 32.5 s. From 275.5 s to 398.0 s, the density oscillates between 0.14 and 0.19 , and then it varies between 0.16 and 0.21 as indicated in Figure 12c.

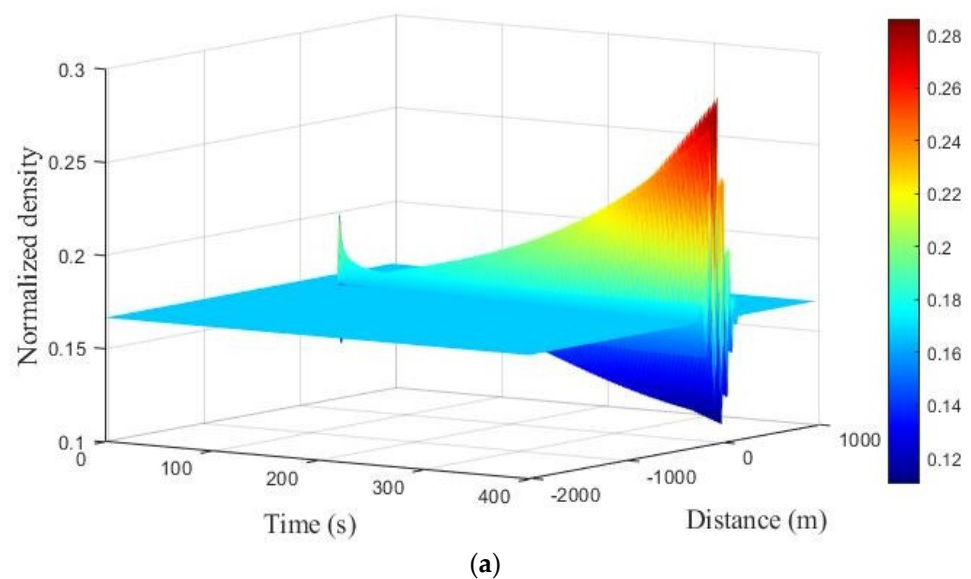


Figure 12. Cont.

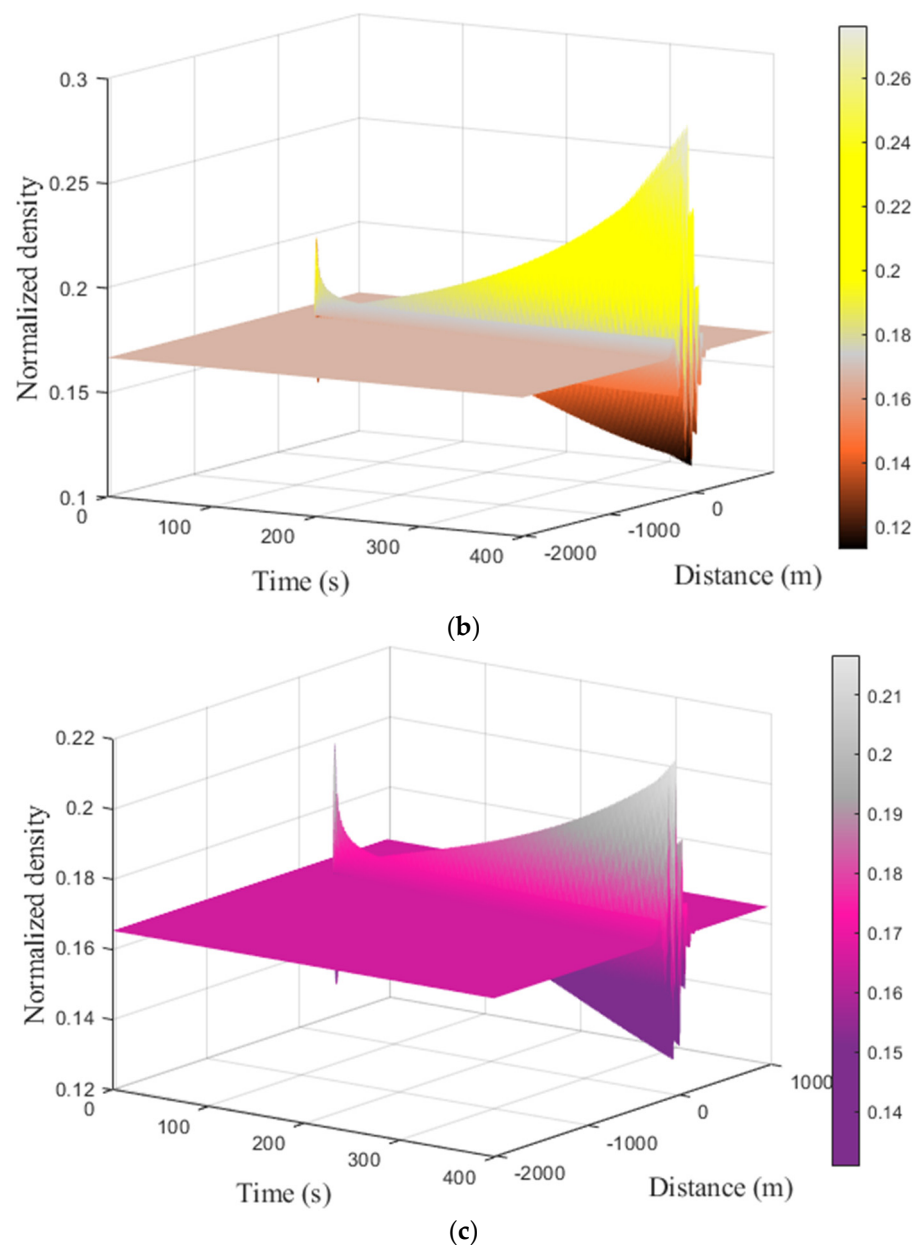


Figure 12. Normalized density for the proposed model with $v_d = 12.50$ m/s over a 3000 m circular road: (a) $PCI = 0$; (b) $PCI = 50$; (c) $PCI = 100$.

Figure 13 gives the normalized density for the proposed model with $v_d = 15.27$ m/s and $PCI = 0, 50$ and 100 . When $PCI = 0$, the density is 0.17 until 31.0 s, increasing to 0.20 at 32.0 s, and then decreasing to 0.13 at 33.0 s. The density oscillates between 0.13 and 0.21 from 266.5 s to 398.0 s, and then it varies between 0.17 and 0.28 as indicated in Figure 13a. When $PCI = 50$, the density is 0.17 until 31.0 s, increasing to 0.20 at 32.0 s, and then decreasing to 0.13 at 33.0 s. The density oscillates between 0.13 and 0.22 from 269.5 s to 398.0 s as indicated in Figure 13b. When $PCI = 100$, the density is 0.16 until 31.0 s, increasing to 0.20 at 32.0 s, and then decreasing to 0.13 at 33.0 s. The density oscillates between 0.13 and 0.20 from 288.5 s to 398.5 s as indicated in Figure 13c.

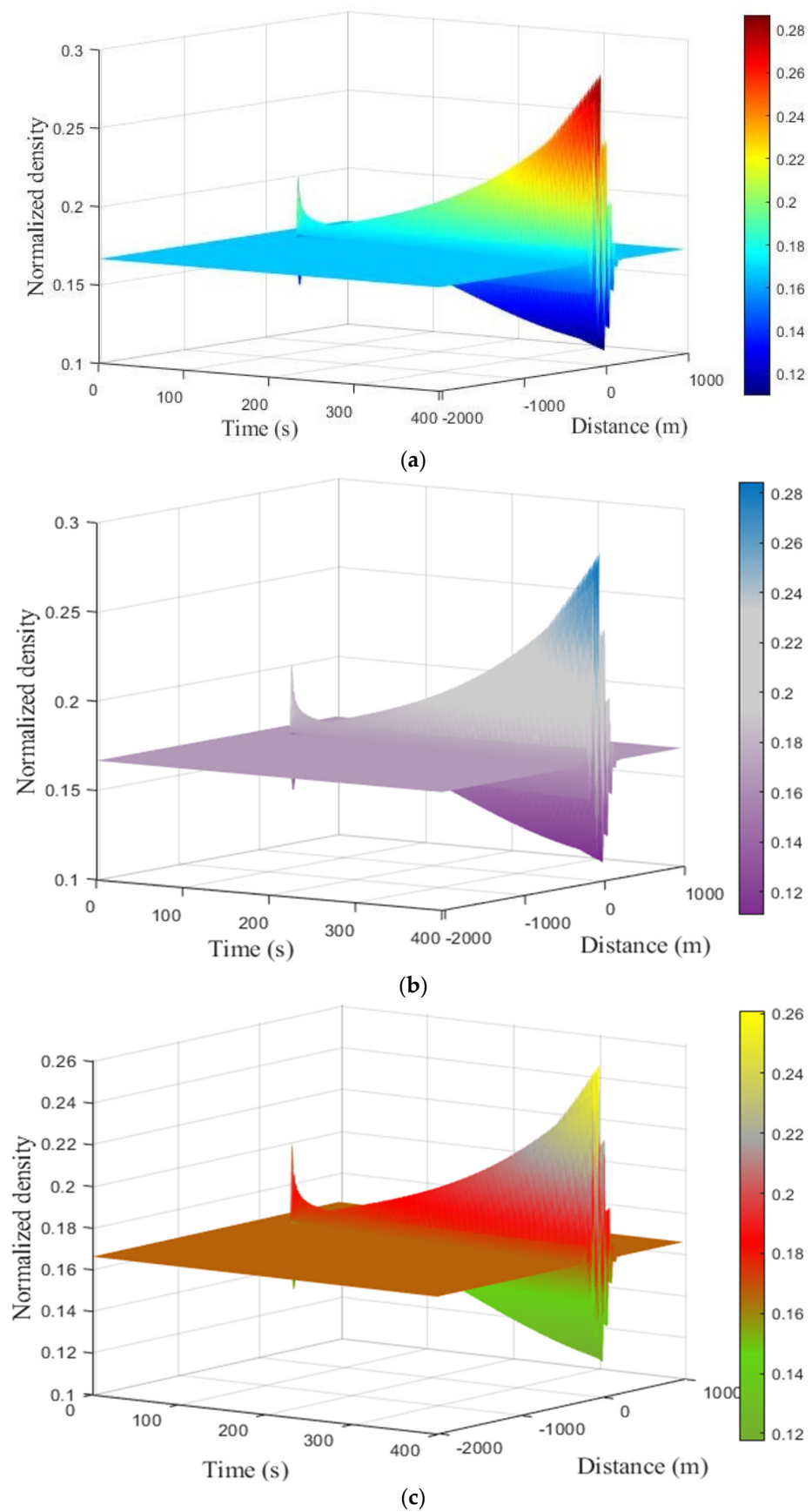


Figure 13. Normalized density for the proposed model with $v_d = 15.27$ m/s over a 3000 m circular road: (a) $PCI = 0$; (b) $PCI = 50$; (c) $PCI = 100$.

Figure 14 gives the normalized density for the ID model with $v_d = 15.27$ m/s and $\delta = 1, 4$, and 20. When $\delta = 1$, the density is 0.15 until 31.0 s, increasing to 0.19 at 32.0 s, and then decreasing to 0.12 at 32.5 s. The density oscillates between 0.14 and 0.16 from 123.0 s to 149.0 s, and then it varies between 0.15 and 0.16 as indicated in Figure 14a. When $\delta = 4$, the density is 0.16 until 31.0 s, increasing to 0.20 at 32.0 s, and then decreasing to 0.13 at 32.5 s. It oscillates between 0.15 and 0.17 from 102.5 s to 149.0 s as indicated in Figure 14b. When $\delta = 20$, the density is 0.16 until 31.0 s, increasing to 0.20 at 32.0 s, and then decreasing to 0.13 at 33.5 s. The density oscillates between 0.15 and 0.17 from 96.5 s to 149.0 s and then it varies between 0.16 and 0.18 as indicated in Figure 14c.

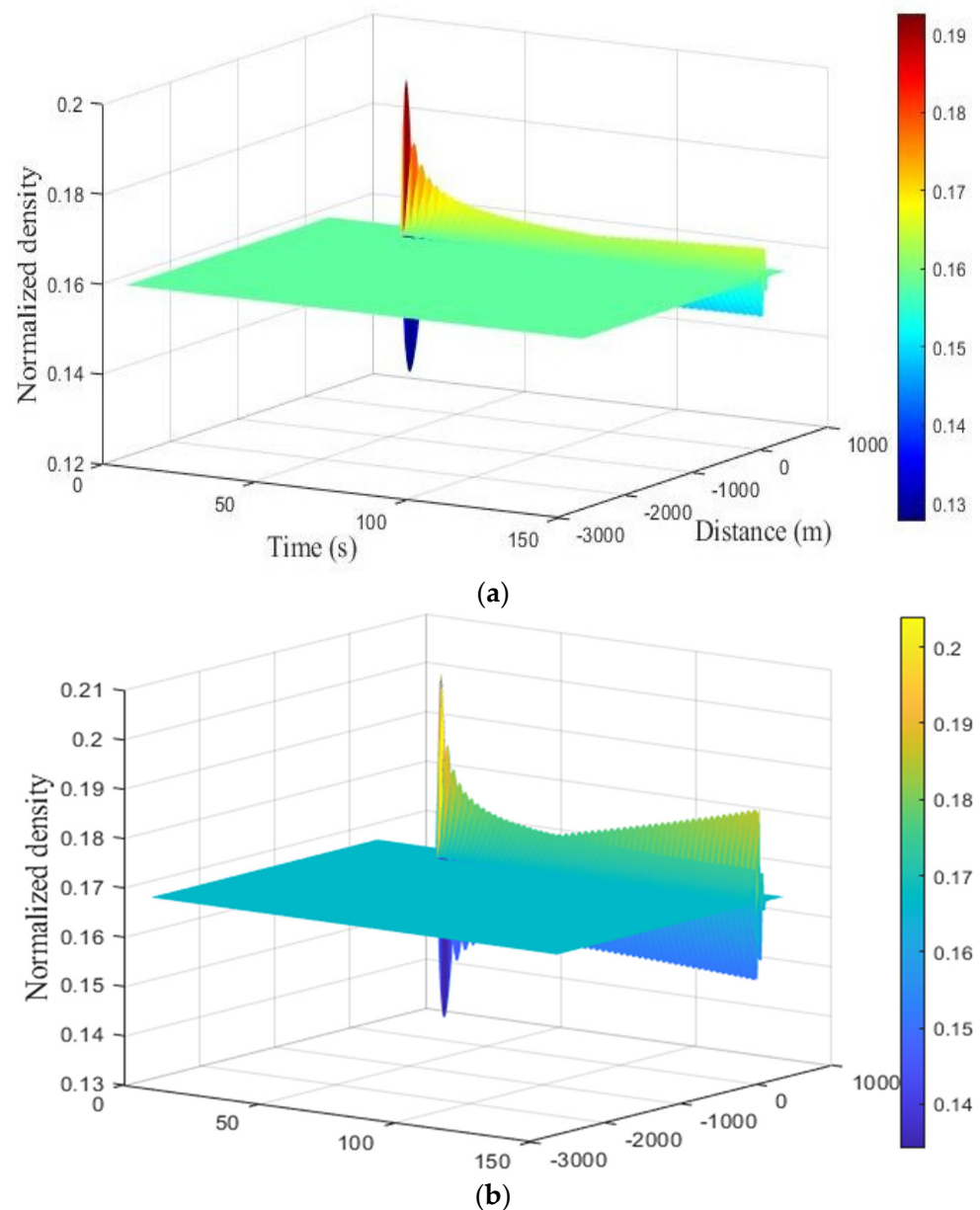


Figure 14. Cont.

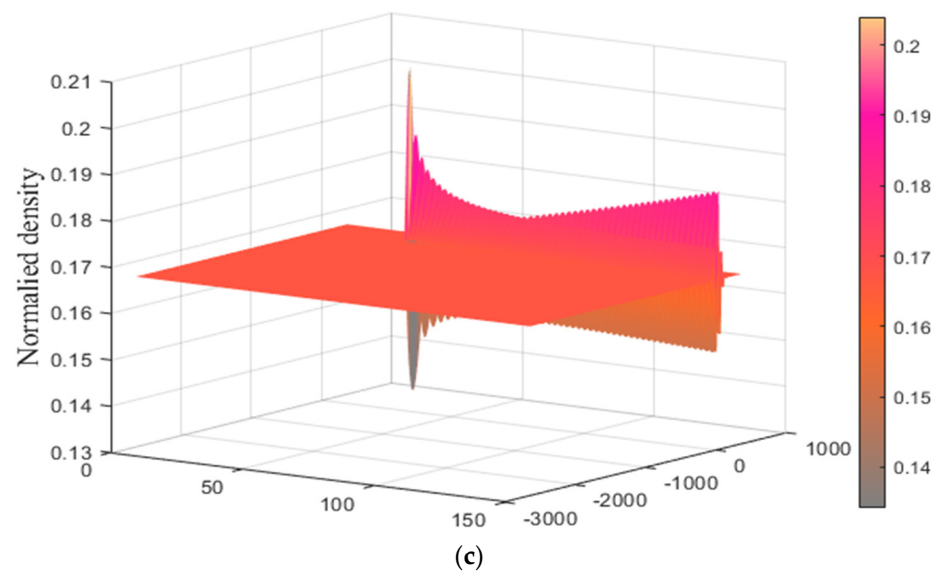


Figure 14. Normalized density behavior for the ID model over a 3000 m circular road: (a) $\delta = 1$; (b) $\delta = 4$; (c) $\delta = 20$.

The results for the proposed model indicate that pavement condition influences traffic flow as expected. In particular, the flow increases with speed as shown in Figures 3–5. The flow with the ID model increases with δ , which is not based on traffic physics. Furthermore, the oscillations in speed and density with the proposed model vary with the PCI and decrease over time as the PCI increases. These results are more realistic as they are based on real parameters such as the PCI. Conversely, the oscillations in speed and density with the ID model are the result of an arbitrary fixed parameter, and they increase over time as δ increases with no justification. This is an inadequate and unrealistic traffic characterization.

6. Conclusions

A microscopic traffic flow model was developed based on pavement condition. The Pavement Condition Index (PCI) was used to characterize traffic behavior. The performance of the proposed model was evaluated and compared with that of the Intelligent Driver (ID) model. The results obtained demonstrate that the proposed model provides realistic traffic flow dynamics. In particular, the traffic flow under excellent pavement conditions ($PCI = 100$) is high while the flow under poor pavement conditions ($PCI = 0$) is low, as expected. Conversely, the ID model has a fixed acceleration exponent which does not reflect the relationship between flow and road condition. Furthermore, the oscillations in speed and density with the proposed model vary according to the pavement condition. They are negligible when the PCI is high, which is expected traffic behavior. In contrast, the ID model produces unrealistic speed and density oscillations based on δ . The results given indicate that the proposed model can be used in traffic simulators for realistic and effective traffic prediction.

The proposed model is a deterministic rather than a probabilistic system. Future research can integrate random variables to provide a probabilistic framework. This will allow the model to deal with the uncertainties and variability in complex traffic environments. Furthermore, it can be implemented for road networks to examine challenging traffic situations and propose solutions. Future research can also consider additional parameters. While PCI is a key factor in traffic flow dynamics, it is important to include other factors such as road emergencies to increase the applicability and improve the accuracy and effectiveness in real-world scenarios. This will contribute to the development of more comprehensive and robust models for traffic flow analysis and management.

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