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Transportation Research Procedia 23 (2017) 174–187

Transportation Research Procedia

www.elsevier.com/locate/procedia

22nd International Symposium on Transportation and Traffic Theory

The Intelligent Driver Model with Stochasticity –New Insights Into Traffic Flow Oscillations

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Abstract

Traffic flow oscillations, including traffic waves, are a common yet incompletely understood feature of congested traffic. Possible mechanisms include traffic flow instabilities, indifference regions or finite human perception thresholds (action points), and external acceleration noise. However, the relative importance of these factors in a given situation remains unclear. We bring light into this question by adding external noise and action points to the Intelligent Driver Model and other car-following models thereby obtaining a minimal model containing all three oscillation mechanisms. We show analytically that even in the subcritical regime of linearly stable flow (order parameter $\epsilon < 0$), external white noise leads to spatiotemporal speed correlations "anticipating" the waves of the linearly unstable regime. Sufficiently far away from the threshold, the amplitude scales with $(-\epsilon)^{-0.5}$. By means of simulations and comparisons with experimental car platoons and bicycle traffic, we show that external noise and indifference regions with action points have essentially equivalent effects. Furthermore, flow instabilities dominate the oscillations on freeways while external noise or action points prevail at low desired speeds such as vehicular city or bicycle traffic. For bicycle traffic, noise can lead to fully developed waves even for single-file traffic in the subcritical regime.

Peer review under responsibility of the scientific committee of the 22nd International Symposium on Transportation and Traffic Theory.

Keywords: car-following model, traffic oscillations, flow instability, acceleration noise, action points, spectral intensity, fluctuations, correlations, order parameter, bicycle traffic

1. Introduction

Traffic flow oscillations, including stop-and-go traffic, are a common phenomenon in congested vehicular traffic [11, 1, 14, 23, 28]. Conventionally, this phenomenon is described in terms of linear or nonlinear string or flow instabilities [26, 13, 21] which are typically triggered by a local persistent perturbation, e.g., lane changes near a bottleneck [1]. In another approach, the flow oscillations are traced back to indifference regions of the human driver [6, 4] or to finite perception thresholds leading to abrupt acceleration changes at discrete "action points" [25, 24]. Related to this are finite attention spans [7, 22]. It has also ben proposed that the oscillations may be caused by event-oriented changes of the driving style switching, e.g., between

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Peer review under responsibility of the scientific committee of the 22nd International Symposium on Transportation and Traffic Theory.
10.1016/j.trpro.2017.05.011

"timid" and "aggressive" [9], or, related to this, by over- and underreactions [27]. Finally, direct external additive or multiplicative acceleration noise (e.g., caused by perception errors) is postulated to drive the oscillations. This line of reasoning is typically modelled by cellular automata (e.g., [18]) which need some sort of stochasticity, anyway, for a proper specification. However, there are also approaches to incorporate acceleration noise into time-continuous car-following models leading to stochastic differential equations [22, 19]. One of the simplest approaches is the "Parsimonious Car-Following Model" (PCF model) [10] which adds white acceleration noise to the free-acceleration part of Newell's car-following model with bounded acceleration [8] and, as [22], also provides explicit numerical stochastic update rules by integrating the stochastic differential equation over one time step.

While all of the above approaches can explain certain observations, it remains an open question whether these approaches are connected with each other, and if so, in which way. Another open problem is to identify the situations where oscillations are caused predominantly by flow instabilities, by indifference regions, or by noise.

In this contribution, we bring light into these questions by proposing a general scheme for adding noise and indifference regions (in form of action points) to a class of deterministic acceleration-based car-following models. Suitable underlying models include the Intelligent Driver Model (IDM) [20], the Full Velocity Difference Model (FVDM) [5], or Newell's car-following model [12] with bounded accelerations [8]. In this way, we obtain a minimal model containing all three mechanisms which we then analyze analytically and numerically. The focus is on the generic instability mechanisms and their relative importance rather than on specific car-following models.

The rest of the paper is organized as follows: In the next section, we specify the minimal model. In Section 3, we introduce the order parameter ϵ denoting the relative distance to linear string instability and analytically derive, as a function of ϵ, the statistical fluctuation properties induced by white noise, including spectral, modal, and overall intensity of the vehicle gap and speed fluctuations, and the associated spatiotemporal correlations. In the Sections 4 and 5, we investigate the oscillation mechanisms for high-speed and low-speed traffic (cars and bicycles, respectively), and compare the results with experimental observations. Finally, Section 6 concludes with a discussion.

2. Model Specification

We consider general stochastic time-continuous car-following models of the form

$$\dot{v}_n = f(s_n, v_n, v_l) + \xi_n(t), \quad \langle \xi_n(t) \rangle = 0, \quad \langle \xi_n(t)\xi_m(t') \rangle = Q\delta_{nm}\delta(t-t'). \tag{1}$$

Here, $f(\cdot)$ denotes the acceleration function of the underlying car-following model for vehicle n as a function of the (bumper-to-bumper) gap s_n, the speed v_n, and the leader's speed v_l. Time delays in the independent variables representing reaction times such as in Newell's Car-Following Model [12] are allowed. The white acceleration noise $\xi_n(t)$ is completely uncorrelated in time and between vehicles (the Kronecker symbol $\delta_{nm} = 1$ for $n = m$ and zero, otherwise; $\delta(t - t')$ denotes Dirac's delta distribution), and has the intensity Q. Model (1) can be seen as a simplistic special case of the Human Driver Model (HDM) [22]. Notice that, when starting with a deterministic initial state $v_n(0)$ at $t = 0$, integration of the stochastic differential equation (1) leads, in the limit $t \to 0$, to a Gaussian speed distribution whose expectation and variance are given by (see, e.g., [2])

$$\langle v_n(t) \rangle = v_n(0) + ft, \quad \langle (v_n(t) - (v_n(0) + ft)^2 \rangle = Qt \tag{2}$$

where the variance is independent of f. Consequently, Q has the unit $\mathrm{m}^2/\mathrm{s}^3$. By chosing a deterministic car-following model with the ability for string instability, e.g., the Intelligent Driver Model (IDM) [20] or the Full Velocity Difference Model (FVDM) [5], the model (1) contains the two oscillation-inducing factors noise and string instability. We introduce the third factor, indifference regions in the form of action points, by updating the deterministic acceleration to the actual value given by $f(\cdot)$ only, if

$$\left| f(s_i(t), v_i(t), v_l(t)) - f(s_i(t'), v_i(t'), v_l(t')) \right| > \Delta a, \quad \Delta a \sim U(0, \Delta a_{\max}). \tag{3}$$