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Traffic disruption and recovery in road networks

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HIGHLIGHTS

- Domain wall model used to explain disruption and recovery processes in road networks.
- Both one-dimensional systems and two-dimensional networks studied.
- Domain wall model includes interactions of multiple walls during recovery.
- Domain wall predictions in good agreement with cellular automata simulations.

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ABSTRACT

We study the impact of disruptions on road networks, and the recovery process after the disruption is removed from the system. Such disruptions could be caused by vehicle breakdown or illegal parking. We analyze the transient behavior using domain wall theory, and compare these predictions with simulations of a stochastic cellular automaton model. We find that the domain wall model can reproduce the time evolution of flow and density during the disruption and the recovery processes, for both one-dimensional systems and two-dimensional networks.

1. Introduction

The study of vehicular traffic has played an increasingly significant role in non-equilibrium statistical mechanics over recent years. A number of approaches, such as car following models, cellular automata and optimal velocity models have been applied to model traffic. The study of the impact of traffic bottlenecks, or *defects*, on network performance are of particular interest.

Bottlenecks are a frequent cause of traffic congestion. Many bottlenecks are *sitewise*, meaning the location of the bottleneck does not change in time. Such bottlenecks can be further classified as either slowdown-regions or lane-reductions. Ramps, slopes and bad weather act effectively as slowdown bottlenecks, whereas vehicle breakdown, illegal parking and road-work are the main causes of lane reduction. One could also view intersections with traffic lights as sitewise time-dependent bottlenecks. The impact of slowdown bottlenecks for the asymmetric simple exclusion process (ASEP) was studied in Refs. [1–3]. Such studies have been extended to freeway networks; see for example Refs. [4–9].

Compared to the extensive study of slowdown bottlenecks, there are few studies of lane reduction. Recently, Ref. [10] studied the traffic characteristics near a lane reduction bottleneck using the optimal velocity model. In this model there is a merging section upstream of the bottleneck where vehicles slow down and make asymmetric lane changes in order to merge into the unblocked lane. It was found that the road capacity increased as the length of the merging section decreased, and as the maximum speed in that section increased. In effect, the merging area acts as a slowdown bottleneck. A similar

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scenario was studied in Ref. [11] using a two-lane cellular automaton model with a localized lane-reduction bottleneck. It was found that the capacity at the bottleneck was slightly smaller than that of a single-lane road, and the density distribution in the merging area depended on its length. A similar study was performed in Ref. [12].

It is of considerable theoretical and practical interest to study the impact of bottlenecks using macroscopic evolution equations, in order to obtain robust results which are independent of the specific microscopic details inherent in any particular model/system. Domain wall (DW) theory [13,14] is a phenomenological approach which has proved very successful in explaining both the stationary and transient behavior for ASEP, and is expected to be applicable to a rather general class particle transport systems.

The aim of the current work is to study the impact of lane-reduction defects on both one-dimensional and two-dimensional traffic networks. For the stationary state, we study the impact of such defects on both the phase diagram and the fundamental diagram. In the transient regime, we discuss an extended domain wall model which allows multiple domain walls to exist in the system simultaneously. We then compare the time evolutions of density and flow produced by the domain wall model with those produced by simulating a stochastic cellular automaton (CA) model.

For one-dimensional systems, the CA model we use consists essentially of two parallel NaSch models, with the addition of simple lane-changing rules. For two-dimensional networks, we used the NetNaSch model [15].

The remainder of this paper is organized as follows. We study one-dimensional systems in Section 2. After giving a brief outline of the CA model and discussing the key features of the DW theory, we study the phase diagram and fundamental diagram of the perturbed system. We then use the domain wall model to study the response of the system to the imposition, and subsequent removal, of a defect (lane-reduction bottleneck), and then compare these results with those of our CA simulations. In Section 3 we extend these studies to a two-dimensional network. Finally, we conclude with a discussion in Section 4.

2. One-dimensional traffic system

In this section we study a one-dimensional traffic system of length L. A localized defect (traffic disruption) is imposed on the system at location x, for duration D. Prior to the imposition of the defect, the system is in a stationary state. We consider two distinct models of this scenario, both of which are spatially and temporally discrete; a cellular automaton, based on the Nagel–Schreckenberg model, and a simple random walk model of domain walls.

2.1. NaSch model with defects

The CA model studied here consists of two lanes oriented in the same direction. The dynamics along each lane is governed by the Nagel–Schreckenberg (NaSch) model [16], and additional rules governing lane-changing are imposed. Each lane is discretized into cells, each of which can be either occupied by a vehicle or empty. Each vehicle can move $0, 1, 2, \ldots, v_{\max}$ cells per time step, depending on local traffic conditions. A random unit deceleration is applied with probability p_{noise}. We use open boundary conditions, and so the density in the network is not directly controlled. On each lane, at each time step, vehicles are inserted into the system with rate α. The precise inflow mechanism used on each lane is that described in Ref. [17], to ensure that the unperturbed system can reach the maximum flow regime. A vehicle at the end of the system which is traveling with sufficient speed is allowed to exit with an output probability β.

Two alternative distinct types of lane changing rules were considered. The first type of lane changing corresponds to the *dynamic lane changing* rules described in Ref. [15]. In essence, these rules allow a vehicle which could achieve a higher speed by making a lane change to change lanes provided no vehicle in the neighboring lane is forced to suddenly decelerate. We shall refer to these lane changing rules as *symmetric*, since they apply symmetrically to left-to-right and right-to-left lane changes.

When the system is in stationarity, we impose a localized blockage in cell x of the left lane. A second set of lane changing rules are implemented to allow vehicles to navigate past the defect. We refer to these rules as asymmetric lane changing, since they allow lane changes from left to right but not right to left. In our model, vehicles are not aware of the defect until they arrive at the cell immediately upstream of it. Vehicles in the left lane then change to the right lane whenever the adjacent cell is unoccupied, which may cause vehicles in the right lane to decelerate. Once such vehicles pass the defect, they may change back to the left lane or not, according to the rules of symmetric lane changing.

In order to understand the effect on the system of the lane reduction we will focus on the density and flow. The density of cell i at time t is simply the indicator for the event that cell i is occupied at time t. This quantity is a stochastic process, and we denote its expected value by $\rho(i, t)$. The density of the cell containing the defect is not defined. For concreteness, we define the right-lane cell adjacent to the defect to belong to the downstream subsystem. The density of the system $\rho(t)$ is then simply the arithmetic mean of $\rho(i, t)$ over all cells $1 \le i \le L$.

Similarly, the flow from cell i to cell $i+1$ along a given lane at time t is simply the indicator for the event that a vehicle crosses the boundary between cells i and $i+1$ during the tth time step. We denote its expected value by $J(i, t)$. The flow per lane $J(t)$ is then simply the arithmetic mean of $J(i, t)$ over all cells $1 \le i \le L$.[1] For simplicity, henceforth we shall take it as

[1] In practice, in our simulations we measured the flow only every 100 cells.