Linking synchronized flow and kinematic waves *

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Abstract. This paper shows that including the effects of lane-changing activity in kinematic wave theory reveals the physical mechanisms and reproduces the main empirical features that motivated Kerner's three-phase theory. This is shown using a hybrid representation of traffic flow where lane changes are treated as discrete particles with realistic accelerations embedded in a continuous multilane kinematic wave stream. We show that this parsimonious four-parameter model reproduces the three phases identified by Kerner, including phase transitions and jam formation. We conclude that synchronized flow and wide-moving jams differ only in their lane-changing spatiotemporal patterns, but obey the same conservation laws and boundary conditions. Freeway segments with one, two and three junctions are analyzed.

1 Introduction

Kerner's three-phase theory [1] was introduced for explaining complex traffic features, such as the capacity drop [2–6], hysteresis [7], stop-and-go waves [8–13] and other complex traffic patterns [14–16]. It has been the subject of intense debate in recent years [17]. In particular, there is no consensus on (i) whether or not the so-called synchronized flow should be considered as a separate phase, and (ii) whether traffic jams arise spontaneously or are caused by bottlenecks. This paper shows that lane-changing activity is at the core of the matter, and helps to provide an answer to these important questions.

Recently, a multilane hybrid (MH) model [18] that requires only four observable parameter has been shown to explain most of the above-mentioned traffic complexities. These parameters are the triangular fundamental diagram (ie, free-flow speed, u, wave speed, w and jam density, κ), and a behavioral parameter, τ, in time units, which could be roughly interpreted as the time to complete a lane change maneuver.

The MH model is based on the effects of "disruptive lane-changing maneuvers"; ie, a lane-changing vehicle acts as a moving bottleneck on its target lane while it accelerates to the speed prevailing on that lane. The ensuing disruption creates voids in the target traffic stream and triggers other lane changes. These lane changes, in turn, create other voids. And voids reduce capacity! It turns out that this simple physical principle explains the capacity drop on bottlenecks caused by lane-drops, moving obstructions and merge bottlenecks; see [18,19].

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This paper shows that the MH model reproduces the main features of three-phase theory. To this end, §2 describes the input data for the MH model; §§3 to 6 present simulations of the scatter in the fundamental diagram, the outflow from wide-moving jams, the "catch effect" and the spontaneous emergence of jams, respectively. Finally, a brief discussion is included in §7.

2 Input data

All the numerical experiments in this paper assumed the following parameter values: $\tau = 4$ sec, $u = 112.7$ km/h (70 mph), $w = -22.5$ km/h (-14 mph) and $\kappa = 139.7$ vpkpl (225 vpmpl). We used a time-step of Δt= 0.6 sec, but the results are independent of Δt.

We have assumed that all the lane-changing particles correspond to cars with a maximum acceleration given by $a = a_0(1-v/v_{max})$, where v is the car's current speed, while v_{max} and a_0 are the car's maximum speed and acceleration at zero speed, respectively. We chose a car with average performance features, such that $v_{max} = 123.8$ km/hr (76.9 mph) and $a_0 = 3.4$ m/s^2 (11.17 ft/s^2).

3 Scatter in empirical fundamental diagrams

Empirical traffic data gathered from loop-detectors exhibit a wide scatter in the congested branch of the fundamental diagram. In fact, synchronized flow was introduced for reproducing this scatter.

Our results indicate that the scatter is a combination of two factors: (1) a disruptive lane change creates congestion upstream and free-flow downstream; (2) different lanes may be in different regimes at a given point in time; eg, left lane in free-flow and right lane in congestion. In both cases the aggregate state will fall inside the fundamental diagram. The precise location of this point in the fundamental diagram depends on the proportion of time spent in each state.

To illustrate this, Fig. 1 presents the simulated fundamental diagrams collected at 5 evenly-spaced locations $(x_0, \ldots x_4)$ on a three-lane freeway segment

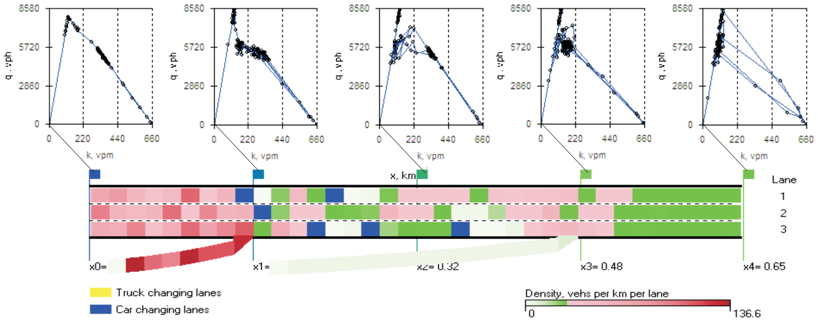

Fig. 1. Fundamental diagrams collected at locations $x_0, \ldots x_4$.

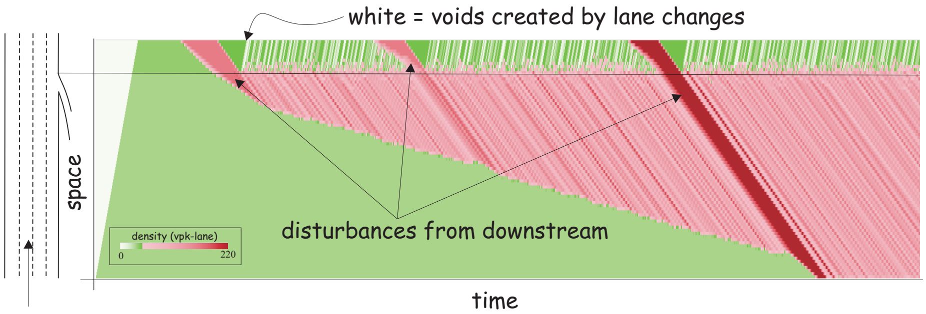

Fig. 2. Time-space density map showing the simulation of the “catch effect”.

with two on-ramps. The simulation consisted in varying on-ramp demand rates and introducing exogenous moving jams, in order to create a wide variety of traffic conditions on all detectors. The aggregation interval was 30 seconds. It can be seen an important scatter at $(x_1, \ldots x_4)$. We conclude that the free-flow state created by a disruptive lane change (void) and the congested state upstream of it produces aggregate states inside the fundamental diagram and may explain the scatter in empirical observations.

4 The “catch effect”

It has been observed that when a disturbance coming from upstream propagates through an initially uncontested on-ramp, it induces a bottleneck that can last for long periods of time.

The time-space density map resulting from the simulation of the “catch effect” is shown in Fig. 2. Three disturbances from downstream were exogenously introduced in the simulation. Notice that after the passage of the first disturbance through the on-ramp, disruptive lane-changing maneuvers appear. This can be seen as white areas in the figure, which represent the voids in flow that a disruptive maneuver produces in traffic stream. As a consequence, the bottleneck discharge rate decreases, which explains the capacity drop and why congestion gets caught at the on-ramp and does not vanish.

5 Outflow from wide-moving jams

Empirical evidence indicates that the inflow to a wide-moving jam, q_{in}, is consistently higher than the outflow from the jam, q_{out}; ie,

$$q_{in} > q_{out}. \tag{1}$$

To the author’s acknowledge, existing traffic flow models capture this effect by means of additional exogenous parameters; ie, this phenomenon is imposed to the models rather than being a consequence of the underlying theory. In the MH

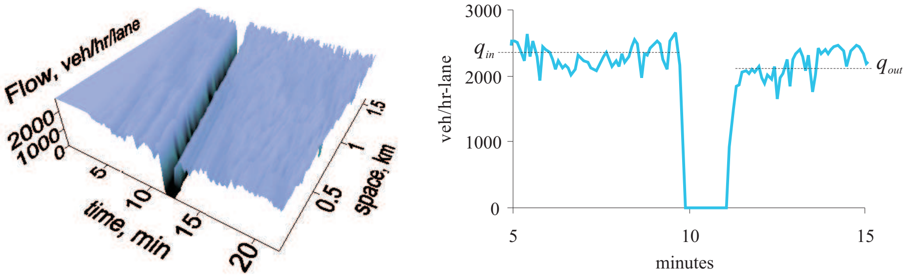

Fig. 3. Simulation results of a wide-moving jam propagating through a three-lane freeway: spaciotemporal pattern of the mean flow across lanes (left); lane-average flow vs time at location $x = 0.8$ km (right).

model, however, a lower outflow is obtained naturally because of lane-changing maneuvers taking place near the downstream front of the jam.

The simulation results of a wide-moving jam propagating through a three-lane freeway is shown in Fig. 3. The left part of the figure shows the spaciotemporal pattern of the mean flow across lanes, where it is clear that the jam propagates with constant speed on both ends, as observed empirically. The right part of the figure shows a cross-section of this surface at location $x = 0.8$ km, where it is evident how condition (1) is satisfied.

6 Stop-and-go at on-ramp bottlenecks

Complex traffic patterns have been observed at on-ramp bottlenecks, most notably stop-and-go waves and the spontaneous emergence of wide-moving jams. The following experiments show how these complex features arise naturally in the proposed theory. Fig. 4 shows the propagation of disturbances across three on-ramps. Notice that wide-moving jams propagate at a constant speed and tend to get wider as they propagate through the on-ramps. This is in qualitative agreement with the observations in [1].

Fig. 5 shows the emergence stop-and-go waves on a freeway segment with a single on-ramp. Freeway demand was held constant at 90% of its capacity. Notice how the level of on-ramp demands determines both the frequency and magnitude of stop-and-go waves.

7 Discussion

This paper has showed that the effects of lane-changing activity near bottlenecks may be the main cause of traffic instabilities. Our results suggest the following physical explanation to traffic instabilities at merge bottlenecks: on-ramp queues

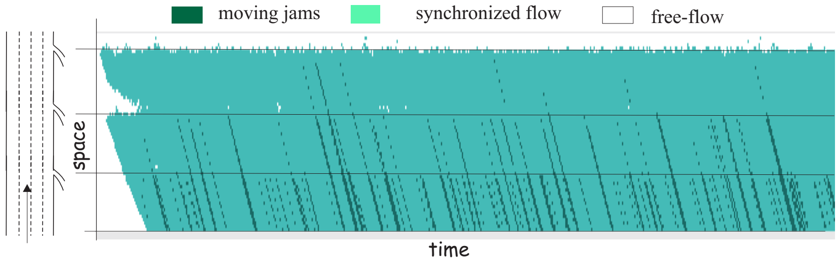

Fig. 4. Propagation of disturbances across three on-ramps.

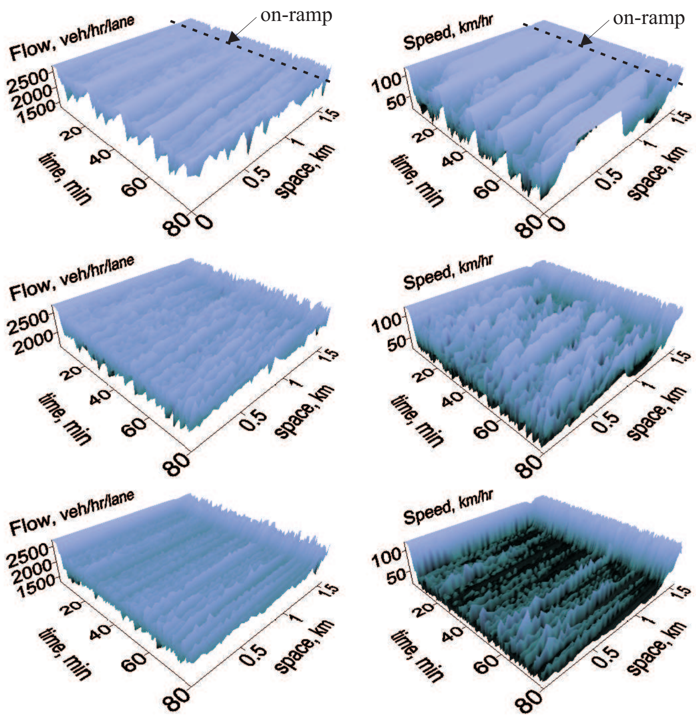

Fig. 5. Stop-and-go at on-ramp bottlenecks for low on-ramp demand (top, 400 veh/hr), medium on-ramp demand (middle, 700 veh/hr) and high on-ramp demand (bottom, 1100 veh/hr). On-ramp at x=1.2 km.

determine the speed at which traffic enters the freeway. This is approximately the same speed at which shoulder-lane vehicles will start their lane-changing maneuvers. Therefore, the lower the speed of entering traffic the greater the voids created by lane changes from the shoulder lane and the greater the losses in capacity. It also follows that the stop-and-go waves observed at on-ramp bottlenecks may be caused by changes in traffic conditions at the on-ramp.

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