Jams, Waves, and Clusters

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Have you been suffering from traffic jams lately and asking yourself why freeways are no free ways anymore? After several great advances in traffic theory, Korean physicists (1) have now offered an interpretation of a recently discovered state of congested traffic, called "synchronized" traffic (2). Their fluid-dynamic simulations can be a useful tool for an optimization of traffic flow on motorways.

When Nagel and Schreckenberg presented their cellular automaton model of traffic flow in 1992 (3), allowing for a more than real-time simulation of the entire road system of large cities, they probably did not anticipate the flood of publications and the enthusiasm among scientists that they would cause on the subject of traffic theory. By treating huge numbers of interacting vehicles similar to classical many-particle systems, physicists have recently added a lot to a better understanding of traffic flow. The mathematical tools that they use, stemming mainly from statistical physics and non-linear dynamics, have proved their interdisciplinary value many times. This includes concepts reaching from self-organized criticality and phase transitions up to the kinetic theory of gases, fluids, and granular media.

In traffic, drivers try to maximize their own utilities (i.e. velocity, safety, and comfort) within the constraints imposed by physical limitations and traffic rules. Under certain conditions, their competitive, non-linear interactions give rise to the formation of collective patterns of motion like traffic jams. The various observed phenomena on freeways are surprisingly rich: Apart from free traffic and extended traffic jams behind bottlenecks, there are localized clusters (small moving jams) and stop-and-go waves. In addition, Kerner and Rehborn (2) have recently discovered a hysteretic phase transition from free traffic to a form

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of congested traffic (mostly appearing close to on-ramps) that had not been identified in more than 40 years of traffic research, they say. Kerner and Rehborn call it "synchronized" traffic because of the synchronization of velocities among lanes. However, the probably more characteristic feature is its high flow in spite of the breakdown of velocity, which is in contrast to traffic jams. Downstream of the ramp, the breakdown of velocity eventually relaxes to free traffic in the course of the freeway. Another interesting property is the wide scattering of synchronized traffic states, when plotted in the flow-density plane, which differs from the quasi-linear density-dependence of free traffic flow.

Lee *et al.* (1) have now suggested an explanation for this hysteretic phase transition. They simulated freeways, including on- and off-ramps, with a fluid-dynamic traffic model that is closely related to the Navier-Stokes equations for viscous, compressible fluids. However, it contains an additional relaxation term describing adaptation of average vehicle velocity to an equilibrium velocity, which monotonically decreases with growing density. In comparison with previous simulation studies, Lee *et al.* used another velocity-density relation and a considerably different set of parameters. By a temporary peak in the on-ramp flow, they managed to trigger a form of oscillating congested traffic that is propagating upstream, but pinned at the location of the ramp (see Fig. 1a). They call it the "recurring hump" state (RH) and compare it to autocatalytic oscillators. Free traffic would correspond to a point attractor and the oscillating traffic state to a stable limit cycle. In terms of non-linear dynamics, the transition corresponds to a Hopf bifurcation, but a subcritical one, since the critical ramp flow depends on the size of the perturbation.

Lee *et al.* point out that free traffic (FT) survives the assumed pulse-type perturbation of finite amplitude, if the ramp flow is below a certain critical value. However, once a RH state has formed, it is self-maintained until the ramp flow falls below another critical value which is smaller than the one for the transition from FT to the RH state. This proves the hysteretic nature of the transition. Moreover, Lee *et al.* could show the gradual spatial transition from the RH state to free flow downstream of the ramp. They also managed to reproduce the synchronization among neighboring freeway lanes as a result of lane changes.

Therefore, they suggest that their model can describe the empirically observed first-order phase transition to synchronized traffic. The two-dimensional scattering of synchronized traffic states is understood as a result of the fact that the amplitude of the oscillating traffic state depends on the ramp flow.

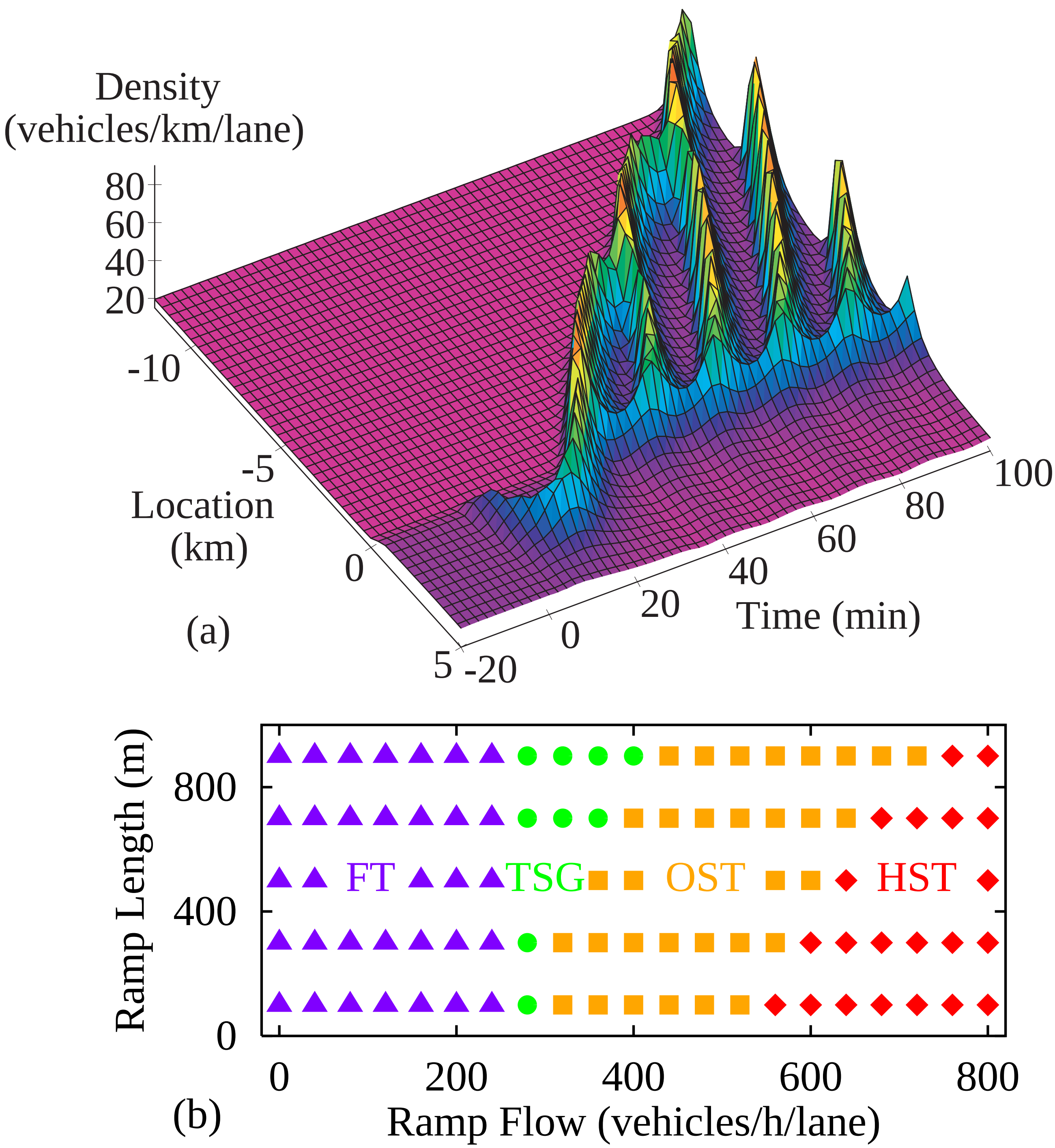
Although the interpretation of synchronized traffic by Lee *et al.* does not *quantitatively* agree with the observations, in various respects it comes pretty close to reality. Meanwhile, a more complete explanation has been offered (4). Above all, the findings are also of great practical importance. A more detailled analysis shows that there is a whole spectrum of different states that can form at ramps. Their occurence decisively depends on the inflow as well as the ramp length (see Fig. 1b). This is not only relevant for an appropriate dimensioning of ramps, but also for an optimal on-ramp control.

In conclusion, traffic theory is presently more interesting than ever before. Recent advances have yielded a better understanding of traffic flow phenomena as well as realistic and fast simulation models. Scientists are now prepared to design on-line controls for efficient traffic optimization, calculate the environmental impact of congestion, and develop methods for traffic forecasts.

References

1. H. Y. Lee, H.-W. Lee, D. Kim *Phys. Rev. Lett.* **81**, 1130 (1998).
2. B. S. Kerner and H. Rehborn *Phys. Rev. Lett.* **79**, 4030 (1997).
3. K. Nagel and M. Schreckenberg *J. Phys. I France* **2**, 2221 (1992).
4. D. Helbing and M. Treiber, *Phys. Rev. Lett.* **81**, 3042 (1998) and preprint cond-mat/9809324.

FIGURES


Density
(vehicles/km/lane)
80
60
40
20
-10
-5
Location
(km)
0
5
-20
0
20
40
60
80
100
Time (min)
Ramp Length (m)
800
400
0
FT
TSG
OST
HST
0
200
400
600
800
Ramp Flow (vehicles/h/lane)

(a)

(b)

FIG. 1. (a) Formation of the recurring hump state (RH) on a freeway for the model and parameters used by Lee *et al.* Since we used free rather than periodic boundary conditions, the inflow at the on-ramp located at 0 km did not need to be balanced by an off-ramp, which is more realistic. The constant ramp flow of 318 vehicles per hour and lane causes a higher vehicle density downstream of the ramp. Nevertheless, free flow pertains, until a short perturbation of the ramp flow occurs at time 0 min, which moves downstream in the beginning. However, with growing amplitude, the perturbation changes its propagation speed, reverses its direction, and finally induces another, bigger perturbation, when passing the ramp. This process repeats again and again, in this way generating the oscillating RH state. When passing the ramp, the perturbations continue their way upstream, until they merge with one of the humps that were born later.

(b) Phase diagram of the various traffic states that can occur close to an on-ramp in the presence of small perturbations in the ramp flow. We show the dependence of the traffic states on the ramp flow and the ramp length for a flow of 1800 vehicles per hour and lane on the freeway. For small ramp flows, free traffic (FT) survives. At higher inflows, two different kinds of RH states can build up, either triggered stop and go waves (TSG) or oscillatory synchronized traffic (OST). High ramp flows are associated with a homogeneous form of synchronized congested traffic (HST).

Hyperlinks

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