Stop-and-Go Science

By better understanding traffic flow, researchers hope to keep down highway congestion

By PETER WEISS

Welcome to Los Angeles. The year is 2020. The traffic is, well, worse.

Average commuting times are twice what they were in the 1990s. Drivers endure a stop-and-go crawl over almost half the miles they travel. Peak speeds on the region's roads have tumbled. The average rush-hour, roadway speed is 24 miles per hour.

These bleak predictions from the Southern California Association of Governments may paint a more troubled picture for L.A. than what's expected for many metropolitan areas. However, the rest of the world's cities won't be far behind.

Officials at all levels of government are sorting through a queue of proposals to lessen congestion. They include, for example, better mass transit systems, new road-use fees to influence driver choices, and construction of separate highways for cars and trucks.

Meanwhile, scientists and engineers around the globe are trying to figure out how to cram more vehicles onto the existing roadways without putting highway speeds into a nosedive. "We can't just build more and more roads, so basically we have to try to use the existing capacity more efficiently," says Peter Molnar, a traffic scientist at Clark Atlanta (Ga.) University.

It's a two-pronged undertaking in which researchers are generating mathematical and computer models of traffic flow and at the same time devising ways to reduce congestion.

Some of the new mathematical models, advanced mainly by physicists, depict traffic as more complex and unpredictable than traditional traffic experts, mainly civil engineers, believe it to be. These models have sparked intense controversy.

Other, relatively simple models, which are based on computer simulations rather than differential equations, are winning acceptance for their ability to generate artificial traffic networks that behave like real ones.

Researchers have also begun applying their findings in new ways, such as combining simulations with actual traffic data to predict and avert delays. In the next few years, traffic-forecasting systems linked to intelligent highway controls, such as on-ramp metering lights, will become more common, the scientists say. Then, the benefits of their investigations should start to kick in.

Traffic-flow research is undergoing "a renaissance due to technological advances," especially in computing, says Bernardo A. Huberman of Xerox PARC in Palo Alto, Calif.

Highways Agency

Highways Agency/Giles Barnard

Speed limits change in response to traffic conditions on M25, a highway encircling London that has devoted a segment of its 117-mile length to testing technologies to improve traffic flow. Behind the scenes, people in a control room use video cameras to monitor traffic along M25 and connecting roads. By setting speeds and giving other directions (inset shows a sign on a local road), the pilot system has improved traffic flows, cut accident rates, and lessened pollution, say London police.

Armed with powerful mathematical and computational tools, scientists interested in traffic patterns have flooded the literature with creative representations. "You have a whole zoo of models," says Michael Schreckenberg of the University of Duisburg in Germany. "It seems that every second paper defines a new model," he jokes.

Computer-based traffic models simulate virtual vehicles that motor by the hundreds or thousands through an artificial highway network. The simulations emerge from a more general category of computer models known as agent-based systems, or cellular automata.

In such models, multitudes of agents interact in an artificial environment. A limited set of rules governs each agent's behavior, making possible endless scenarios, from the evolution of weird life forms to the rise and fall of artificial societies (SN: 11/23/96, p. 332).

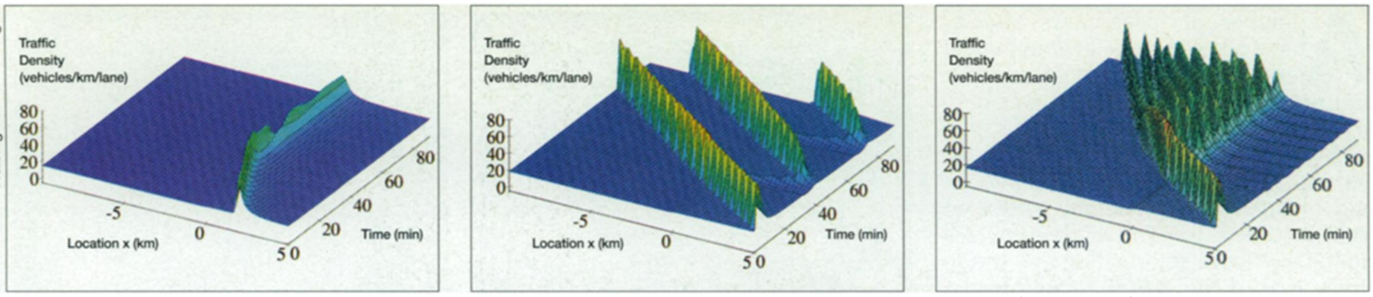
"We're trying to boil this whole complicated thing down to a few [traffic] rules," says Kai Nagel of the Los Alamos National Laboratory and the Santa Fe Institute, both in New Mexico.

In the early 1990s, he and Schreckenberg introduced cellular-automata models to traffic-flow research. Since then, such simulations have grown in popularity. Although the models are built from simple rules, the collective behavior of the antlike subunits can become complex. The units in computer-driven cellular-automata models can suddenly organize themselves into distinctive patterns (SN: 8/13/94, p. 109), some of which resemble highway congestion.

In contrast to the cellular-automata methods, a more top-down, conceptual approach to traffic relies on equation-based models. These typically depict the aggregate characteristics of traffic, such as average speed and traffic density. Researchers often build such simulations by adapting physical models of the behavior of gases and liquids.

Using this approach, some scientists have recently proposed a new picture of traffic. They argue that vehicle flows can suddenly and spontaneously turn sluggish or crystallize, a process like the transition of a freezing liquid to a solid. These phase transformations of traffic can appear in some parts of the flow but not in others.

An even better analogy points to the flow of granular materials, such as sand or salt, says Schreckenberg. In a pile of sand that's partly damp and partly dry,



Helbing et al./U. Stuttgart

Traffic congestion fluctuates in waves shown in graphs of solutions to a mathematical model of highway flow near an on ramp (at x=0). Patterns include bunching just next to the ramp (left), stop-and-go traffic in which cars reach full speed between jams (center), and stop-and-slow traffic in which cars don't regain full speed before reaching the next congestion wave (right). Which pattern, or traffic phase, forms depends on how many vehicles pour in from upstream (negative x *direction) and from the on ramp.*

slightly damp grains tend to clump up. Even dry sand can undergo sudden transformations, such as an avalanche.

Recognizing that unlike molecules or sand, cars move under the control of people, physicists have added expressions to their equations to take into account drivers' abilities to anticipate conditions and attempt to avoid crashes.

Spontaneous transformations of traffic, as seen in their models, indicate previously unrecognized complexity in highway flow, according to Shreckenberg and other statistical physicists. Understanding it requires the concepts and equations of a relatively new branch of mathematics known as nonlinear dynamics, they say.

Since the late 1970s, researchers have tapped nonlinear dynamics as a tool for understanding a wide range of phenomena, including chemical reactions that progress through phases (SN: 2/21/98, p. 116) and boom-or-bust population cycles of various organisms (SN: 9/10/94, p. 164).

If scientists can make sense of this new-found highway complexity, they may have a better chance of smoothing it out. "If you know the dynamic properties of traffic patterns, then you can predict what happens with these patterns in the future," says Boris S. Kerner of automaker DaimlerChrysler in Stuttgart, Germany. Such warning would allow traffic controllers to activate strategies to prevent sudden transitions or break up undesirable phases once they have formed, he adds.

Kerner is a leading advocate of this new view of traffic as a complex system. He and Hubert Rehborn, also at the DaimlerChrysler Research Center, have found evidence that traffic can transform between several different phases, similar to the way that water changes between vapor, liquid, or ice states.

The researchers analyzed traffic data collected from sensors built into German autobahns. Besides freely flowing cars and a full-scale traffic jam, they first reported in 1996 a third state, which they dubbed synchronized traffic flow. Under certain circumstances, cars would suddenly all slow down to roughly the same speed and tend to stay in lane, indicating that the traffic had jelled into a type of unified, moving mass.

Further data revealed that the synchronous phase allows waves of dense traffic to pass upstream along the highway and leads to stop-and-go driving conditions. Kerner reported this finding in the Oct. 26, 1998 Physical Review Letters.

He concludes, "With our experimental results . . . we have understood the nonlinear properties of real traffic flow."

Despite Kerner's declaration, other researchers are still adding new pieces to the puzzle. Huberman and Dirk Helbing of the University of Stuttgart found another highly coordinated, dense traffic state in a cellular-automata simulation of mixed cars and trucks. They described it in the Dec. 24/31, 1998 Nature.

The researchers reported finding evidence of their simulated traffic phase in Dutch highway data. "This state is quite favorable because it's associated with a high flow," Helbing explains.

More recently, Helbing and other colleagues came up with a new analysis of traffic that defines six phases. Besides free flow and traffic jam, the researchers identify four phases of congestion, all characterized by waves of rising and falling vehicle density. The phases may overlap with Kerner's synchonized traffic state.

The new findings distinguish the phases by how often waves pass through the stream of vehicles and how much the density drops off between waves. In a phase called a "pinned localized cluster," for instance, an enduring but very localized bunching haunts the immediate vicinity of an on ramp.

The researchers have found evidence for each of the phases in data from European autobahns. Their analysis appears in the May 24 Physical Review Letters.

Instead of the excitement of the physicists who have created it, the new picture of traffic has aroused the ire of traditional traffic researchers. Traffic engineers are particularly disturbed by the physicists' notion that traffic flow can spontaneously break down into a slow-moving or stopped state.

"When congestion arises for no apparent reason, this just means that its cause has not been identified," asserts Carlos F. Daganzo of the University of California, Berkeley. There are many possible causes to choose from, such as accidents, merges, stalled cars, and slowpoke drivers.

Studies of actual traffic by Michael J. Cassidy, also of Berkeley, show that congestion recurs reliably at the same bottlenecks along highways. Uncovering the causes usually suggests cures, such as ramp metering or redesigning the geometry of a stretch of highway. However, "if congestion really does form for reasons we cannot pinpoint, then dealing with congestion in those instances would be much harder," Cassidy says.

In the May 19 Transportation Research Part A, Cassidy, Daganzo, and Robert L. Bertini, also of Berkeley, explain how ordinary bottlenecks could account for Kerner's data without invoking nonlinearity or self-organizing complexity.

Daganzo also notes that engineers have long been aware of phase transitions in traffic, such as the onset of a jam, but have simply used different words to describe the phenomena. The recent models, for the most part, rediscover and relabel well-known concepts and observations in their field, he and other engineers claim.

The complicated, nonlinear models also fail the test known as Occam's razor, says Paul Nelson, a physicist at Texas A&M University in College Station. That is, the simplest theory that explains a phenomenon is the best theory. The complex models "clearly can be tuned to produce about any effect one wishes to produce," Nelson argues, and thus may have little to do with real traffic.

In response to the modelers who envision improving the flow of vehicles on highways, Carroll J. Messer, also of Texas A&M, offers a word of caution. He notes that the capacity of a typical American freeway has grown steadily, from 1,800 vehicles per lane per hour in 1965 to about 2,400 per lane per hour today. "It's because of better vehicle performance and driver performance and because our roads are better," he says. Messer, however, wonders if that figure can realistically go much higher. There are limits to the degree to which motorists' driving can be coordinated, he says.

A number of researchers already have taken their cellular-automata models on the road to monitor and predict traffic throughout an extensive area. Schreckenberg and his colleagues have made such a model for Duisburg, a city of half a million people, and blended the simulation with data from road sensors. The model provides up-to-the-minute information on traffic flows within the city via the Internet (http://traf2.uni-duisburg.de/OLSIM). Visitors to the Web site see a color-coded map indicating which streets are congested. Click on a street, and more-detailed information pops up, such as the number of cars per minute.

By winter, a much more ambitious plan to simulate traffic on the major arteries of Europe's most densely populated region should be complete, Schreckenberg says. In the German state of North Rhine-Westphalia, there are 10 million people within a diameter of 68 kilometers. He says, "It's comparable to Los Angeles. It has no real center." Much of the truck traffic between Western and Eastern Europe rumbles across the area's highways.

Beyond minute-by-minute updates on traffic flows, which should begin in August, the model will also provide 1-hour traffic forecasts by the end of November, Schreckenberg says. "In 1 minute, you can calculate for the next hour," he explains. "You just accelerate the simulation."

These predictions would allow drivers with access to the Internet to plan their speediest route.

Traffic engineers at Texas A&M are also blending the real and the simulated, but with a different goal. In a laboratory at the Texas Transportation Institute, they link simulations of vehicle traffic to computerized traffic controllers used in the field. The controllers, in turn, simultaneously drive both real signals and signs, such as traffic lights, and simulations of such indicators.

"We could use simulated control or flip a switch and use the real control system," Messer says. "It's just like replacing a heart in surgery."

By running simulations through the actual equipment, engineers get to see how well their control strategies handle various scenarios, such as accidents or construction. Test runs help them iron out bugs that could make traffic worse rather than better, Messer says.

Cellular-automata simulations are also beginning to influence long-range traffic planning. The Transportation Analysis and Simulation System (TRANSIMS), which Nagel and other researchers have been developing at Los Alamos National Laboratory, tracks the movements, over a 24-hour period, of a population of software agents matched statistically to a city's residents. The simulation takes into account minute details about streets, traffic signs, bus and bike routes, and neighborhood demographics. It reveals overall and local traffic-flow patterns while monitoring each individual's contribution.

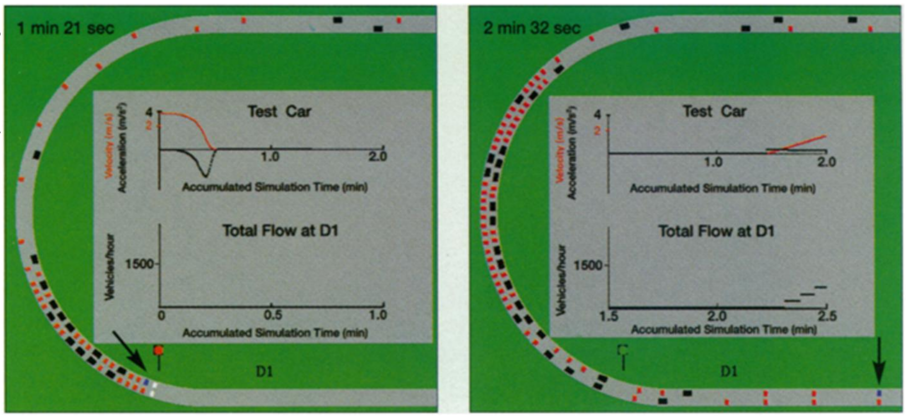
A TRANSIMS simulation of part of Dallas has influenced road-construction planning in the city. The project's scientists hope by next year to model the entire city of Portland, Ore.

While disagreeing on what it takes to understand traffic, researchers seem to concur that it's a comprehensible phenomenon that will yield to their efforts. To theorists such as Schreckenberg, who helped launch cellular-automata traffic models about 8 years ago, the ultimate triumph would be to unite cellular-automata and equation-based models under one conceptual umbrella—"a universal theory of traffic," he calls it.

"Development is going very fast at the moment," Schreckenberg says. He expects that in the next 8 years, they'll find such a theory.

Many of the experts also seem optimistic that applying their understanding of traffic, either by increasing the flow of vehicles on existing roads or improving planning for future highway growth, will make a difference in the battle against congestion. □

Second Institute of Theoretical Physics/U. Stuttgart



A simple cellular-automata simulation of traffic flow: Cars (red) and trucks (black) queue at a red light (red dot at lower left) and then resume movement when the light turns green. Graphs track behavior of a test vehicle (arrow) and total traffic flow. An active demonstration can be viewed at http://www.theo2.physik.uni-stuttgart.de/treiber/MicroApplet/index.html.