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NEIGHBORHOODS IN TRAFFIC

HOW COMPUTER SCIENCE CAN CHANGE THE LAWS OF PHYSICS

ABSTRACT

How can we explain and analyze the world around us? That is the key question any natural scientist has to answer when considering a complicated system. It is a standard approach in physics to reduce the underlying behavior to a set of rules that is as simple as possible, but still able to reproduce the observed behavior as well as possible. This has a close connection to neighborhood technologies: Very often, these rules are based on simple laws that govern the local interaction between neighboring basic components, and produce the global behavior in an emergent fashion. Once these laws are understood, one can try to exploit them for technological applications.

The possibilities of modern computer science have given a new perspective to this approach. In principle, we can program any set of physical laws for a complex system and then observe the resulting behavior – at least in simulations. What is more, we can go beyond figuring out absolute laws of physics, and *change* these laws, simply by programming different sets of rules for interaction.

In recent years, tremendous progress has been made in understanding the dynamics of vehicle traffic flow and traffic congestion by interpreting traffic as a multi-particle system. This helps to explain the onset and persistence of many undesired phenomena, e.g. traffic jams. It also reflects the apparent helplessness of drivers in traffic, who feel like passive particles that are pushed around by exterior forces; one of the crucial aspects is the inability to communicate and coordinate with other traffic participants.

The following article describes a distributed and self-regulating approach for the self-organization of a large system of many self-driven, mobile objects, i.e. cars in traffic. Based on short-distance communication between vehicles, and ideas from distributed algorithms, we consider reaction to specific traffic structures (e.g. traffic jams.) Building on current models from traffic physics, we were able to develop strategies that significantly improve the flow of congested traffic. Results include fuel savings of up to 40% for cars in stop-and-go traffic.

1. INTRODUCTION

1.1 Physics and Computer Science

A standard scientific method for *understanding* complicated situations is to analyze them in a top-down, hierarchical manner. This also works well for organizing a large variety of structures; that is why a similar approach has worked extremely well for employing computers in so many aspects of our life. On the other hand, our world has grown to be increasingly complex. The resulting challenges have become so demanding that it is impossible to ignore that a large variety of systems has a very different structure. The stability and effectiveness of our modern political, social and economic structures relies on the fact that they are based on decentralized, distributed and self-organizing mechanisms.[1]

Until not very long ago, scientific efforts for studying computing methodologies for decentralized complex systems ~~have~~#had been very limited. Traditional computing systems are based on a centralized algorithmic paradigm: data is gathered, processed, and the result is administered by one central authority. Each of these aspects is subject to obstructions. On the other hand, "Living organisms [...] are to be treated as dynamic systems and contain all infrastructure necessary for their development, instead of depending on coupling to a separate thinking mind. We call this computing paradigm *organic computing* to emphasize both organic structure and complex, purposeful action."[2] The importance of organic computing has been ~~motivated~~#explained as follows: "The advantages of self-organizing systems are obvious: They behave more like intelligent assistants, rather than a rigidly programmed slave. They are flexible, robust against (partial) failure, and are able to self-optimize. The cost of design decreases, because not every variant has to be programmed in advance."[3]

Two important properties of organic computing systems are self-organization and emergence. We follow the definition of Tom De Wolf and Tom Holvoet[4] ~~who give the following definitions~~: "Self-organization is a dynamical and adaptive process where systems acquire and maintain structure themselves, without external control" and

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1 For a non-fiction bestseller see James Surowiecki, *The Wisdom of Crowds* (London: Doubleday, 2004).

2 Organic Computing Initiative. 2004. A novel computing paradigm. http://www. organic-computing. org.

3 Christian Müller-Schloer, Hartmut Schmeck and Theo Ungerer, *Organic Computing – A Paradigm Shift for Complex Systems* (Basel: Birkhäuser Verlag, 2011).

4 Tom De Wolf and Tom Holvoet, "Emergence versus Self-Organisation: Different Concepts but Promising when Combined," *Engineering Self-Organising Systems* 3464 (2005), p. 1–15.

"[a] system exhibits emergence when there are coherent emergents at the macro-level that dynamically arise from the interactions between the parts at the micro-level. Such emergents are novel w.r.t. the individual parts of the system."[5]

In the following we will show how to combine aspects of distributed computing and #distributed communication (introduced in Section 1.2) with a new concept of algorithms and data structures, in order to deal with the challenge of influencing a very important complex system: traffic. Clearly, road traffic by itself (as introduced in Section 1.3) exhibits both properties postulated by de Wolf. Vehicles interact on the micro-level without external control by local interactions (self-organized) and due to these micro-level interactions, structures at the macro-level arise, such as traffic jams or convoys.

1.2 Distributed Communication

A critical aspect for influencing a complex system, no matter whether in a centralized or decentralized manner, is making use of distributed communication, which is becoming more and more feasible ~~by~~#through the advance of modern technology. Today's applications for distributed systems rely on unicast or multicast communication. Prominent and well-known examples are Client-Server-Applications like web browsing. When mobile ad-hoc networks (MANETs) first came up, research concentrated on efficient routing to keep up the existing communication paradigm. By increasing the number of nodes and introducing dynamics in the network ~~due to~~#by means of node mobility or switching nodes on and off in a large multi-hop network, routing based on addresses became a hard challenge. In the meantime, systems have grown larger, to the point where they consist of thousands of cheap battery-powered devices that organize themselves. This has ~~been considered~~#resulted in a new research field called *sensor networks*. Limitations of bandwidth, computing power and storage in sensor networks drive the corresponding communication paradigm. While these systems need to be designed for frequent node failures, redundancy was introduced in the network, decreasing the importance of single nodes and addresses. The stringent separation of the lower communication layers has also become open for discussion, as it introduces computational and networking overhead especially when identification of nodes loses importance. A recent survey article by Coulson et al.[6] provides an overview and a large number of more

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5 Ibid.

6 Geoff Coulson, Barry Porter, I. Chatzigiannakis, C. Koninis, S. Fischer, D. Pfisterer, D. Bimschas, Torsten Braun, Philipp Hurni, Markus Anwander, Gerald Wagenknecht, S.P. Fekete, A. Kröller, T. Baumgartner, "Flexible Experimentation in Wireless Sensor Networks", *Commun. ACM* 55(1) (2012), p. 82–90.

specific references; for further details, the reader is referred to the abundance on specialized literature.

1.3 Traffic

Traffic is one of the most influential phenomena of civilization. On a small scale, it affects the daily life of billions of individuals; on a larger scale, it determines the operating conditions of all industrialized economies; and on the global scale, traffic has a tremendous impact on the living conditions on our planet, both in a positive and in a negative way.

All this makes traffic one of the most important complex systems of our modern world. It has several levels of complexity, reaching from individual actions of the drivers, over local phenomena like density fluctuations and traffic jams, traffic participants' choice of transport mode and time, regional and temporal traffic patterns, all the way up to long-range traffic development and regulation. Clearly, this tremendous range of complexity also comprises different time scales as well as feedback effects, making traffic a particularly crucial yet difficult area, especially for critical strategic political decisions.

Over the years, tremendous progress has been made in understanding the dynamics of traffic flow and traffic congestion. Arguably the most significant contribution has come from physics, interpreting traffic as a multi-particle system. As described in further detail in Section 2.1, these models explain how the complexity of traffic emerges from the self-organization of individuals that follow simple rules. They also meet the popular appeal of systems of interacting, autonomous agents as problem-solving devices and models of complex behavior. In short, the *decentralized* view, which goes beyond attempts at centralized simulation and control, has improved our understanding of traffic.

1.4 Combining Communication and Mobility

Modern hardware has advanced to the point that it is technically possible to enable communication and coordination between traffic participants, in particular by vehicle-to-vehicle communication[7]. At this point, this is mostly seen as a mere technical gadget to facilitate driving, but the far-reaching, large-scale consequences have yet to be explored. Making use of the technical possibilities of communication and coordination should allow significant changes in the large-scale behavior of traffic as a complex network phe-

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7 E.g., see U.S. Department of Transportation, Research and Innovative Technology Administration, http://www.its.dot.gov/vii/

nomenon. However, combining mobility and communication for coordinated behavior does not only solve problems, it also creates new ones, as it is a challenge in itself to maintain the involved ad-hoc networks, as well as the related information that is independent of individual vehicles.

To this date and the best of our knowledge, the idea of combining the above aspects, i.e. self-organizing traffic by combining ad-hoc networks with distributed decentralized algorithms has received surprisingly little attention. This may be because it requires combining a number of different aspects, each of which has only been developed by itself in recent years: mobile ad-hoc networks, models for large systems of self-driven multi-particle systems, as well as algorithmic aspects of decentralized distributed computing, possibly with elements of game-theoretic interaction.

1.5 Our Work

Our basic idea is to develop a decentralized method for traffic analysis and control, based on a bottom-up, multilevel approach. Beyond the motivations described above, it should be stressed that an aspect of particular relevance is scalability:[8] while the computational effort for a centralized approach increases prohibitively with the number of vehicles, a decentralized method relies on neighborhood interaction of constant size.

2. RELATED WORK ON TRAFFIC

2.1 Traffic and Telematics

As the interest in guiding and organizing traffic has ~~been growing~~#grown over the years, the scientific interest in traffic as a research topic has developed ~~quite~~ dramatically, as the excellent survey *Traffic and related Self-driven Many-Particle Systems* by Dirk Helbing shows.[9] Obviously, research on traffic as a whole is an area far too wide for a brief description in this short overview; we focus on a particular strain of research that is particularly relevant for our proposed work, as it appears to be most suited for simulation and extension to decentralized, self-organizing systems of many vehicles.

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8 André B. Bondi, "Characteristics of Scalability and their Impact on Performance". *Proceedings of the Second International Workshop on Software and Performance – WOSP 2000*. p. 195. doi:10.1145/350391.350432; Mark D. Hill, "What is Scalability?". *ACM SIGARCH Computer Architecture News* 18 (4) (1990), p. 18.

9 Dirk Helbing, "Traffic and Related Self-Driven Many-Particle Systems," *Reviews of Modern Physics* 73 (2001), p. 1067–1141.

It is remarkable that until the early 1990s, efforts for simulating traffic were based on complex multi-parameter models of individual vehicles, resulting in complex systems of differential equations, with the hope of extending those into simulations for traffic as a whole. Obvious deficiencies of this kind of approach are manifold: First, because the behavior of even just ~~an individual~~#one vehicle is guided by all sorts of factors influencing a driver, the hope for a closed and full description appears hopeless. Second, determining the necessary data for setting up a simulation for a relevant scenario is virtually impossible. And third, running such a simulation quickly hits a wall; even with today's computing power, simulating a traffic jam with a few thousand individual vehicles based on such a model is far beyond reach.

A breakthrough was reached when physicists started to use a different kind of approach. Instead of modeling vehicles with ever-increasing numbers of hidden parameters, try to consider them as systems of many particles, each governed by a very basic set of rules. As Kai Nagel and Michael Schreckenberg ~~managed to show~~#showed, even a simple model based on cellular automata can produce fractal-like structures of spontaneous traffic jams, i.e. complex, self-organizing phenomena.[10] Over the years, these models[11] were generalized to two-lane highway traffic,[12] extended for simulating commuter traffic in a large city,[13] and have grown[14] to the point of being used for real-time traffic forecasts for the 2250 km of public highways in the German federal state of North Rhine-Westphalia.[15]

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10 Kai Nagel, Michael Schreckenberg, "A Cellular Automation Model for Freeway Traffic," *Journal de Physique* I France 2 (1992), p. 2221–2229.

11 Kai Nagel, "High-Speed Simulation of Traffic Flow," (Ph.D. diss., Center for Parallel Computing, Universität zu Köln, Germany, 1995).

12 Marcus Rickert, Kai Nagel, Michael Schreckenberg, Andreas Latour, "Two-Lane Traffic Simulation on Cellular Automata," *Physica* A 231 (1996), p. 534–550.

13 Marcus Rickert, Kai Nagel, "Experiences with a Simplified Microsimulation for the Dallas/Fort Worth Area," *International Journal of Modern Physics* C 8 (1997), p. 133–153.

14 Kai Nagel, "Cellular Automata Models for Transportation Applications," *Proc. 5th Int. Conf. Cellular Automata for Research and Industry* Vol. 2493 (2002), p. 20–31.

15 Oliver Kaufmann, Kai Froese, Roland Chrobok, Joachim Wahle, Lutz Neubert, Michael Schreckenberg, "Online Simulation of the Freeway Network of NRW," *Traffic and Granular Flow '99*, ed. Dirk Helbing, Hans J. Herrmann, Michael Schreckenberg, and Dietrich. E. Wolf (Berlin: Springer, 2000), p. 351–356. Andreas Pottmeier, Sigurdur Hafstein, Roland Chrobok, Joachim Wahle, Michael Schreckenberg, "The Traffic State of the Autobahn Network of North Rhine-Westphalia: An Online Traffic Simulation," *Proc. 10th World Cong. and Exh. on Intell. Transp. Syst. and Serv.* Doc. Nr. 2377 (2003). See also www.autobahn.nrw.de and Kai Nagel, "Traffic Networks," *Handbook of Graphs and Networks – From the Genome to the Internet*, ed. Stefan Bornholdt and Heinz Georg Schuster (Berlin: Wiley-VCH, 2003), Chapter 11.

A closely related line of research uses an approach that is even closer to particle physics; the paper *Still flowing: approaches to traffic flow and traffic jam modeling*[16] gives an excellent overview of models for traffic flow and traffic jams, with about 150 relevant references. Among many others, particularly remarkable is the approach by Stefan Krauß:. This model reproduces properties of phase transitions in traffic flow, focusing on the influence of parameters describing typical acceleration and deceleration capabilities of vehicles.[17] This is based on the assumption that the capabilities of drivers to communicate and coordinate are basically restricted to avoid collisions, which until now is frustratingly close to what drivers can do when stuck in dense traffic.

Parallel to the scientific developments described above, the interest in and the methods for obtaining accurate traffic data has continued to grow. The employment of induction loops and traffic cameras has been around for quite a while, but despite of enormous investments, e.g., 200 Mio. Euros by the German Federal Ministry for Transport, Building and Urban Affairs (BMVBW) for putting up systems for influencing traffic, the limits on tracking individual vehicles,[18] as well as following particular traffic substructures are obvious. Another development is the use of floating car data. By keeping track of the movements of a suitable subset of vehicles (e.g., taxis in Berlin city traffic), the hope is to get a more accurate overall image of traffic situations, both in time and space.[19] However, even this approach relies on the use of the central processor paradigm, and does not allow the use of ad-hoc networks for the active and direct interaction and coordination between vehicles.

2.2 Traffic as a Self-Organizing Organic System

The structure of traffic is a phenomenon that is self-organizing at several levels.[20] But even though the behavior of and the interaction between motorists has been observed for a long time, the possibilities arising from modern technology allowing direct and

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16 Kai Nagel, Peter Wagner, Richard Woesler, "Still Flowing: Approaches to Traffic Flow and Traffic Jam Modeling," *Operations Research* 51, 5 (2003), p. 681–710.

17 Stefan Krauß, "Microscopic Modeling of Traffic Flow: Investigation of Collision-Free Vehicle Dynamics," (Ph.D. diss., Center for Parallel Computing, Universität zu Köln, 1998).

18 Bundesministerium für Verkehr, Bau und Stadtentwicklung, 2002. Programm zur Verkehrsbeeinflussung auf Bundesautobahnen 2002–2007. http://www.bmvbs.de.

19 Birgit Kwella, Heiko Lehmann, "Floating Car Data Analysis of Urban Road Networks," *Proceedings Computer Aided Systems Theory – EUROCAST '99*, ed. Franz Pichler, Roberto Moreno-Díaz, Peter Kopacek, *Lecture Notes in Computer Science*, vol. 1798 (Vienna: Springer, 2000).

20 For a philosophical discussion of self-organization in multi-level models see also Carlos Gershenson, Francis Heylighen, "When Can We Call a System Self-Organizing?," *Advances in Artificial Life,* 7th European decentralized complex interaction between vehicles has hardly been studied. The only efforts we are aware of combine game theory with traffic simulations – for example, the symposium organized by traffic physicist Schreckenberg with game-theory Nobel laureate Reinhard Selten.[21] However, neither makes use of mobile ad-hoc networks and distributed algorithms in large networks.

Several research projects focus on enhancing traffic flow by distributed methods. A model based on multi-agent systems is described in Ana L. C. Bazzan's and Robert Junges' *Congestion tolls as utility alignment between agent and system optimum*.[22] Depending on local congestion, a dynamic toll is charged to influence the drivers' routing decisions. Camurri et al.[23] propose a distributed approach using Co-Fields#Großschreibung?# for routing vehicles around crowded areas on an urban grid-like road map. Techniques for detecting traffic anomalies are also developed in centralized systems like the *System for Automatic Monitoring of Traffic* proposed by Bandini et al. The system ~~applies~~#uses video cameras which are installed along highways to derive and monitor traffic events over time based on the ~~composed~~#composite view of the cameras.[24]

All these approaches offer methods that try to solve certain problems arising in the field of traffic management. However, they cannot overcome the dilemma of an individual driver: The downside of individual freedom and control is the seemingly hopeless task of controlling a complex system that is highly sensitive to small perturbations. Even centralized control can try to delay the onset of the resulting oscillations – but it cannot remove the inherent instability of the overall system.

2.3 Our Approach

We have pursued a distributed and self-regulated approach for the self-organization of a large system of many self-driven, mobile objects, i.e., cars in traffic. Based on methods for mobile ad-hoc networks using short-distance communication between vehicles, and

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Conference, ECAL 2003 (September 14–17, 2003), ed. Wolfgang Banzhaf, Thomas Christaller, Peter Dittrich, Jan T. Kim, Jens Ziegler, *Lecture Notes in Computer Science*, vol. 2801 (2002), p. 606–614.

21 Michael Schreckenberg, Reinhard Selten, *Human Behavior and Traffic Networks* (Berlin: Springer, 2004).

22 Ana L. C. Bazzan, Robert Junges, "Congestion Tolls as Utility Alignment between Agent and System Optimum," *Proceedings of the Fifth International Joint Conference on Autonomous Agents and Multiagent Systems* (2006), p. 126–128.

23 Marco Camurri, Marco Mamei, Franco Zambonelli, "Urban Traffic Control with Co-fields," *Proc. of the 3rd Int. Workshop on Environments for Multiagent Systems* (2006), p. 11–25.

24 Stefania Bandini, Davide Bogni, and Sara Manzoni, "Alarm Correlation in Traffic Monitoring and Control Systems: A Knowledge-Based Approach," *Proceedings of the 15th European Conference on Artificial Intelligence* (2002), p. 638–642.

ideas from distributed algorithms, we revise the local physical interaction in congested traffic.

For this purpose, we ~~have~~ developed strategies for dealing with complex and changing traffic situations, such as the improvement of traffic congestion~~s themselves~~. The basic idea is to *change* the way in which individual vehicles respond to each other, and thus overcome the helpless situation of drivers in congested traffic.

3 TECHNICAL DETAILS

3.1 Traffic Simulation

Our approach for improving the flow of traffic is based on the well-known car-following model of Krauß which derives position and velocity of a car from the gap to the predecessor and its velocity.[25] Collisions are avoided based on a safe velocity:

$$\upsilon_{safe} = \upsilon_{pred} + \frac{g - \tau\,\upsilon_{pred}}{\frac{\upsilon + \upsilon_{pred}}{2b}}\,.$$

Here, υ_{pred} is the velocity of the leading vehicle, g the gap to it, τ the reaction time (usually set to 1 s), and b the maximum deceleration. υ_{safe} was proven by Krauß to prevent any collisions. To compute the desired velocity for the next time step, maximum velocity and acceleration a must be considered, too; for a simulation time step Δt, this leads to:

$$\upsilon_{des} = \min[\upsilon_{safe}, \upsilon_{max}, \upsilon + a\Delta t]$$

Finally, actual velocities may be lower than the maximum possible ~~one~~; this is accounted for by subtracting a random value from the current velocity, where *rand* returns a uniformly distributed value between 0 and 1, and σ is a configuration parameter between 0 and 1 to set the amount of randomness, which is usually set to 1.

$$\upsilon_{next} = \max[0, rand(\upsilon_{des} - \sigma a\Delta t, \upsilon_{des})]$$

Krauß's model is also the basis of SUMO [Hertkorn et al. 2002]. SUMO, an acronym for *Simulator of Urban MObility*, is an open-source microscopic traffic simulator developed by

25 Krauß, "Microscopic Modeling of Traffic Flow".

the German Aerospace Center DLR. Despite its name it can also simulate highway traffic. SUMO is used by many different traffic researchers all over the world.[26] ~~Another~~#An alternative is Helbing's *Intelligent Driver Model*.[27] The details are mathematically intricate, but our approach yields similar results.

3.2 Improving the Flow of Highway Traffic

According to previous research,[28] one of the major reasons for collapses of traffic flow on highways, known as traffic jams, is the wide velocity distribution of vehicles. This is well-known to any experienced driver: even in dense traffic, high velocities are possible, as long as all vehicles move at almost the same speed; however, once a random fluctuation has occurred, the average speed drops considerably, and the overall pattern of motion becomes dominated by stop-and-go waves.

Overcoming non-uniform motion is a highly non-trivial matter. It is tempting to strictly enforce a uniform speed that seems to work so well before a collapse occurs. However, making large convoys of vehicles move in lockstep pushes the overall system into a highly unstable state; as a result, the catastrophic consequences of even a small failure or inaccuracy imply tremendous technical, legal, and psychological risks.

We ~~have~~ pursued a ~~softer~~#gentler and more self-regulating alternative, in which individual drivers are still responsible for avoiding collisions. Instead, our driving strategy tries to avoid excessive and unnecessary acceleration when it can be determined that deceleration is imminent. The overall objective ~~was~~#is not only to conserve fuel, but also to homogenize the overall speed distribution; as it turns out, this does improve the average speed. One additional, but equally important requirement was not to depend on the participation of all drivers; instead, even a relatively small system penetration should lead to measurable individual benefits, which constitutes an incentive for using the system and comply with its recommendations.

After a large variety of different tests and simulations, we have developed a recommendation that is based on a convex combination of the desired velocity of the driver and the average velocity of the vehicles.

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26 See http://sourceforge.net/apps/mediawiki/sumo/index.php?title=Projects.

27 Martin Treiber, Dirk Helbing, "Microsimulations of Freeway Traffic Including Control Measures," *Automatisierungstechnik* 49 (2001), p. 478.

28 See also Treiber, "Microsimulations of Freeway Traffic Including Control Measures" and Martin Schönhof, Dirk Helbing, "Empirical Features of Congested Traffic State and Their Implications for Traffic Modeling," *Transportation Science* 41, 2 (2007), p. 1–32.

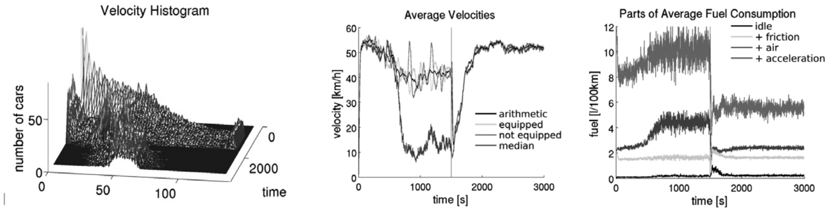

Fig. 1: The average speed increases significantly (top left), while the fuel consumption decreases by about 40% (top right). The key is a much tighter velocity distribution (bottom#center?). This is achieved only through local interaction, without imposing a central speed limit.

$$v_{recommended} = \rho\, v_{desired} + (1 - \rho) v_{average}$$

Here ρ is a coefficient between zero and one. Setting $\rho = 1$ means not to recommend any different velocity ~~than without~~#, i.e. ignore the strategy. On the other hand, setting $\rho = 0$, i.e. ignoring the drivers' desired velocity completely is also counterproductive: whenever a vehicle ahead randomly slows down, vehicles following the strategy will also decelerate, implying that the average velocity converges to zero. Choosing the right compromise between these extremes works amazingly well. A patent[29] was granted in December of 2010. The graphics show typical simulation results, which result in about 40% fuel savings. They also show the key to this improvement: Based on simple local rules, the overall velocity distribution becomes much tighter, without artificially imposing or enforcing a global speed limit. Moreover, the rules provide individual benefits, even for single drivers, implying that the improvement is not dependent on the participation of all drivers. Finally, our approach is inherently *failsafe*: The strategy prevents drivers from unnecessarily accelerating, but drivers continue to be responsible for avoiding collisions (Fig. 1).

CONCLUSIONS

Interpreting vehicles in traffic as interacting physical particles has lead to considerable progress in understanding, analyzing, and even designing traffic scenarios. Our work is

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29 Sándor P. Fekete, Christopher Tessars, Christiane Schmidt, Axel Wegener, Stefan Fischer, Horst Hellbrück, *Verfahren und Vorrichtung zur Ermittlung einer Fahrstrategie*. Patentnummer DE 10 2008 047 143 B4 (2008).

based on a computer science perspective: changing the interaction of individual components of a complex system can lead to a fundamentally different global behavior.

We are convinced that this approach to complex systems will lead to progress in a wide range of other modern areas – ranging from large-scale (and even global) systems, all the way down to nano-scale systems that have been dubbed *programmable matter*. All this promises to yield exciting perspectives for science and technology, employing the concept of neighborhood technologies: The large-scale behavior of complex systems is often the result of simple local rules. Trying to obtain a different (ideally, more efficient) global behavior by dictating strict rules in order to exclude undesired emerging behavior is tempting, but very often futile; for example, outlawing sporadic braking for cars in stop-and-go traffic is no recipe for avoiding traffic jams. Instead, a more subtle, but also more powerful approach based on neighborhood technologies aims at modifying the underlying local rules that lead to the undesired emergent phenomena.

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