Lane-Free Artificial-Fluid Concept for Vehicular Traffic

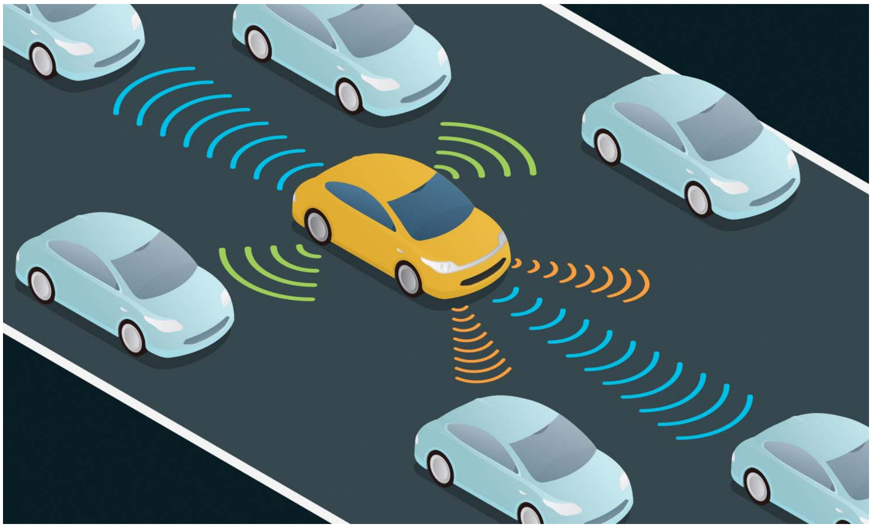
By MARKOS PAPAGEORGIOU, ***Life Fellow IEEE***
Dynamic Systems and Simulation Laboratory, Technical University of Crete, 73100 Chania, Greece

KYRIAKOS-SIMON MOUNTAKIS
Dynamic Systems and Simulation Laboratory, Technical University of Crete, 73100 Chania, Greece

IASSON KARAFYLLIS
Department of Mathematics, National Technical University of Athens, 15780 Athens, Greece

IOANNIS PAPAMICHAIL
Dynamic Systems and Simulation Laboratory, Technical University of Crete, 73100 Chania, Greece

YIBING WANG, ***Member IEEE***
Institute of Intelligent Transportation Systems, Zhejiang University, Hangzhou 310058, China



Vehicular traffic has evolved as a crucial means for the transport of persons and goods, and its importance for the economic and social life of modern society cannot be overemphasized. On the other hand, recurrent vehicular traffic congestion, which appears on a daily basis, particularly in metropolitan areas, around the globe, has been a (increasingly) serious, in fact threatening, problem that calls for drastic solutions. Traffic congestion causes excessive travel delays, substantial fuel consumption and environmental pollution, and reduced traffic safety. Conventional traffic management measures are valuable [1]–[3] but not sufficient to address the heavily congested traffic conditions, which must be addressed in a more comprehensive way that exploits gradually emerging and future ground-breaking capabilities of vehicles and the infrastructure.

Vehicle automation has been a research topic in the past several decades, and the concept of automated highway system (AHS), envisioned in the 1990s [4], triggered a plethora of related results with lasting value (see [5] and [6]). During the last decade, efforts have strongly intensified, notably by the automobile industry and by numerous research institutions, to develop and deploy a variety of vehicle automation and communication systems (VACSs) that are revolutionizing the capabilities of individual vehicles.

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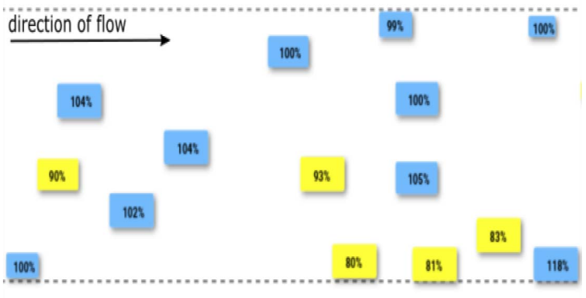

Fig. 1. ***Lane-free traffic.***

VACSs may be distinguished in vehicle automation systems ranging from relatively weak driver support to highly or fully automated driving, and vehicle communication systems enabling vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication. Some low-automation VACSs, such as adaptive cruise control (ACC), are already available in the market.

ACC automatically controls the vehicle speed according to the desired speed selected by the driver, or adjusts the distance in the case of a slower front vehicle. Moreover, numerous companies and research institutions have been developing and testing in real traffic conditions highly automated or virtually driverless autonomous vehicles that monitor their environment and make sensible decisions, not only about car-following, but also about lane changing [7]. There is a variety of methodologies employed for their movement strategies, ranging from artificial intelligence (AI) techniques to optimal control methods. It should be noted that, in this context, the relatively high-risk task of lane changing is particularly challenging, both methodologically and practically [8]–[10].

This article proposes a novel paradigm for vehicular traffic, applicable at high levels of vehicle automation and communication and high penetration rates, as expected to prevail in the not-too-far future. Specifically, we assume that vehicles communicate with each other (V2V) and with the infrastructure (V2I) at sufficient frequency, distance, and bandwidth, and drive automatically, based on their own sensors, communications, and an appropriate movement control strategy. Vehicles may be of various types (e.g., electric or with internal combustion engine) and sizes (cars, vans, buses, trucks, motorcycles) and may have a range of desired (or allowed or achievable) maximum speeds and acceleration capabilities. The proposed concept, called henceforth TrafficFluid for brevity, is based on the following two combined principles.

1) *Lane-free traffic*: Vehicles are not bound to fixed traffic lanes, as in conventional traffic, but may drive anywhere on the 2-D surface of the road, respecting of course the road boundaries (see Fig. 1).
2) *Nudging*: Vehicles communicate their presence to other vehicles in front of them (or are sensed by them), and this may exert a "nudging" effect on the vehicles in front (under circumstances and to an extent to be specified). For example, vehicles in front may experience (apply) a pushing force in the direction of the line connecting the centers of the nudging vehicle and the nudged vehicle in front. Fig. 2 illustrates a possible instance of resulting behavior. Figs. 1 and 2 are snapshots from a preliminary microscopic TrafficFluid simulator, and the % marked on each vehicle reflects its current speed as a percentage of its desired speed. Yellow vehicles drive currently with lower speed than desired due to hindering slower vehicles in front of them, which are therefore nudged, while blue vehicles have a current speed equal to the desired speed or higher, the latter in case they are nudged by vehicles behind them. In Fig. 2, the yellow vehicle has a higher desired speed than the two trucks on its left and right, and therefore it nudges them aside (on the lane-free road), so as to pass between them and accelerate to its desired speed (thus becoming blue).

I. FEATURES, RELATED DOMAINS, AND REQUIRED RESEARCH TOPICS

A. General Features

1) Lane-Based Versus Lane-Free Traffic: For most of human history, roads did not need lanes because of low-speed movements. However, when automobiles came into widespread use during the beginning of the twentieth century, there was a need to separate opposite traffic directions via lane markings on roads and highways to reduce the risk of frontal collisions, while dashed lines, separating parallel lanes on the same traffic direction, were only introduced in the 1950s, along with the rules governing lane-changing. Parallel lanes increase the traffic safety in manual driving, because they simplify the driving task for the human driver; when driving on a lane, the driver needs to monitor only the distance and speed of the front vehicle, with virtually no need to also monitor the own vehicle's left, right, and rear sides. On the other hand, when a driver wishes to change her driving lane, things become more complex and risky, as the driver needs to look for an available gap on the target lane and predict its evolution based on the observed speeds of multiple vehicles (and of her own), while watching at the same time for the distance to the front vehicle. The lane-changing task becomes even more risky in cases of massive lane changes due to lane-drops or merging on-ramps or roads. Indeed, lane changes are responsible for 10% of all accidents [11]. In summary, unidirectional lanes are indispensable in manual driving conditions due to

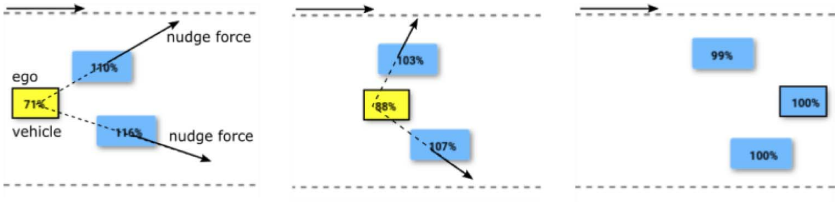

Fig. 2. ***Instance of the nudge effect. The yellow vehicle nudges the slower trucks aside to pass.***

increased safety; on the other hand, the existence of lanes entails the need for lane-changing, which is recognized as an accident-prone maneuver.

The lane width on American interstate highways is 3.7 m, while German Autobahnen feature a lane width of 3.5–3.75 m. Since a medium-sized car has a width of about 1.8 m, and a truck is around 2.5 m wide, we conclude that the lateral occupancy on motorways may be only slightly higher than 50%. Thus, the carriageway capacity could be strongly increased, even if only a part of the void lateral space is used, as in lane-free traffic. This indeed happens (semi-legally), to some extent, in several developing countries, notably in India, where saturation (capacity) flow at traffic lights increases strongly for inhomogeneous traffic with low lane discipline [12]. On top of the static capacity loss due to the need for wide lanes on high-speed highways and arterials with manual driving, additional capacity losses occur due to dynamic phenomena attributed to lane-changing maneuvers. Specifically, lane-changing on highways is a notorious cause for reduced capacity [11] due to increased space occupancy of the lane-changing vehicle and for triggering traffic breakdown at critical traffic conditions. Such phenomena are even more pronounced and detrimental to safety and capacity at locations of increased lateral movements, such as converging or diverging motorways, on- and off-ramps and weaving sections, because of the abrupt and space-consuming lateral displacements required in lane-based traffic.

In a nutshell, unidirectional traffic lanes have emerged in the mid-twentieth century as a necessary measure for improving traffic safety under manual driving, even at the expense of reducing the highway capacity. According to the TrafficFluid concept, there is no need, in the era of high-level vehicle automation and connectivity, to mimic (in fact, there are good reasons to avoid mimicking) the human lane-based driving task. Vehicle sensors and communications enable connected and automated vehicles (CAVs) to monitor fast, simultaneously, continuously, and reliably their close (and even more distant) surroundings on a 360° basis, and to make fast (computer-based) moving decisions. These superbly increased capabilities, compared to human driving, allow for a CAV to "float" safely and efficiently in a stream of other, potentially cooperating, CAVs, based on appropriate movement strategies. Thus, highways, motorways, arterials, and, even urban roads may return to their lane-free structure, regaining the lost capacity and also improving on traffic safety.

Vehicle movement strategies for CAVs are easier to design, safer, and more efficient in a lane-free environment due to smooth 2-D vehicle movement, where accident-prone, hence conservative, laterally "discontinuous" displacements to other lanes become obsolete. In addition, front–back vehicle collisions occurring in manual lane-based driving, sometimes involving dozens of vehicles in a pile-up, may cause more serious damage than their counterpart of side–side collisions that are more likely to occur in lane-free traffic.

Vehicle movement strategies in a lane-free environment may feature variations according to the characteristics of the infrastructure or of encountered other vehicles (e.g., emergency vehicles). In particular, an interesting question concerns the possibility of allowing for a limited percentage of manually driven vehicles, which would call for activation of a special movement strategy for the CAV driving around them.

2) Vehicle Nudging Versus Manual Driving Anisotropy: With regard to the second TrafficFluid principle, nudging, let us first note the (perhaps not merely) verbal similarity with the "nudge theory" by Richard Thaler that earned him the 2017 Nobel Prize in Economics. Thaler introduced the concept of "nudging" people through subtle changes in government policies, such that they do things that are beneficial for them in the long term (e.g., saving money). Back to traffic, a major and indeed "sacred" principle in traffic flow theory is the property of anisotropy in macroscopic traffic flow models [13]–[15]. Macroscopic traffic flow theory started with the seminal work [16], which was based on an analogy of vehicular traffic flow with water flow in open channels. Vehicular traffic indeed exhibits many similar qualitative features, similar to gas in a pipe or water flow in an open channel; similar to water flow, traffic states propagate as waves with a speed different from the fluid particles' speed, and shock waves form when fast vehicles catch up with slower vehicles in front.

On the other hand, there is a major difference between water or gas flow versus vehicular traffic flow, which is due to the fact that vehicle movement (by the action of the human driver) is determined by the happenings downstream (essentially by the distance and speed of the vehicle in

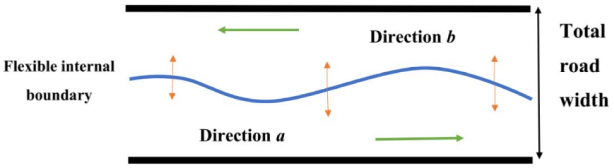

Fig. 3. ***Space–time flexible internal road boundary.***

front), while vehicles behind have normally no impact on a human's driving behavior. In contrast, water or gas flow particles may influence the state of other downstream particles; for example, fast particles may be "pushing" slower particles ahead making them accelerate. The fact that drivers react only to front stimuli is referred to as the anisotropic property of traffic flow and has specific mathematical consequences, for example, that traffic waves cannot propagate faster than vehicles [13].

The proposed nudge effect enables vehicular traffic flow to be deliberately conceived in a variety of possible ways, without the anisotropy restriction imposed by human driving, so as to satisfy appropriate design criteria, for example, increase the flow and the road capacity. Note that nudging is much less interesting if applied to lane-based traffic, where some local inter-vehicle interaction might have a local stabilizing effect or slightly facilitate a lane change of the following vehicle, but this is not comparable to a generalized nudging policy that alters the characteristics of individual vehicle movement and, more importantly, of the emerging traffic fluid in a predictable engineered way. Naturally, nudging must be appropriately designed and limited; for example, nudging may be designed to have no effect if the nudged vehicle has already exceeded its desired speed by a certain percentage, and, certainly, nudging should not lead to road boundary violation or jeopardize traffic safety under any circumstances.

3) Traffic as an Artificial Fluid: According to TrafficFluid, the design of automated vehicle movement strategies should not be based on the legacy of human driving, but should rather be freed from unnecessary restrictions, such as lane discipline and exclusive consideration of downstream conditions, which affect traffic flow efficiency and safety. In fact, vehicle nudging in combination with lane-free flow provide an unprecedented possibility to design (rather than describe or model) the traffic flow characteristics in an optimal way, subject to constraints, but without the need to satisfy anisotropy or other conditions stemming from the era of human driving. In short, we have the problem of designing, for the first time since the automobile invention, the properties of the traffic flow as an artificial fluid, and this is indeed the overarching feature of the TrafficFluid concept.

It is worth noting that the basic prerequisites for a real implementation of the proposed concept are moderate. At the vehicle level, the required movement strategy is likely to be easier to design than strategies currently deployed in autonomous vehicles for lane-based driving (including lane changing), because vehicle movements (including the lateral component) may be smooth (no abrupt lane-changing is required). With regard to onboard sensors and connectivity (V2V and V2I), there are no essential requirements that would exceed current equipment or plans for CAVs. Finally, TrafficFluid does not call for unconventional or expensive new features for the road infrastructure.

It is interesting to note that due to its lane-free character, the TrafficFluid concept leads to incremental capacity increases as a result of incremental road widening, in contrast to the need to widen conventional roads by lane "quanta" to increase their capacity. Thus, limited road widening around problematic bottleneck areas (e.g., on-ramps or strong upgrade or curvature) may be sufficient to dissolve local capacity problems that are those triggering congestion in conventional traffic.

Equally interestingly, the total cross-road capacity of bidirectional roads or highways could be shared flexibly (in space and time) among the two traffic directions according to the prevailing traffic demands in each direction. Flexible capacity-sharing may be achieved via virtual incremental moving of the internal road boundary, which separates the two traffic directions, and corresponding communication to the CAV to respect the changed internal boundary. This way, the carriageway's width portion (and total capacity share) assigned to each traffic direction can be changed in space and time (subject to constraints), as illustrated in Fig. 3, according to an appropriate control strategy, so as to maximize the total traffic efficiency in both directions (see [17] for more details).

It is very interesting to highlight that in contrast to conventional traffic where traffic bottlenecks may be present in either direction independently, the application of internal boundary control implies that bottlenecks concern both traffic directions simultaneously [17]. More specifically, for a bottleneck to be present in a road section, the total bidirectional demand at that section must exceed the total road capacity and this obviously involves both traffic directions. Thus, the total capacity may be shared among the two directions such that congestion is avoided anywhere, except at bottlenecks, that is, locations and time periods where the total bidirectional demand exceeds the total road capacity.

In summary, real-time space-dependent smooth capacity-sharing on existing road infrastructure, facilitated by the lane-free movement of automated vehicles, would enable an unprecedented level of infrastructure exploitation and correspondingly strong mitigation of traffic congestion.

B. Related Domains

As the proposed concept is original, there is, as far as we are aware, no technical literature addressing issues directly related to it. Nevertheless, it is worth pointing out some domains and works that may contain useful elements for the development of the proposed traffic environment.

To start with, the extended domain of vehicle automation, including lane-based vehicle platooning, AHS, and more recent developments (see [4]–[10]), provides a solid and fruitful basis for the development of lane-free and nudged vehicle movement strategies, as required in the new concept. The extension of known 1-D notions, such as vehicle platooning and string stability, to the lane-free 2-D case opens up new options, such as vehicle flocking or snake-like platoon movement on the 2-D road surface.

The low lane discipline and vehicle size diversity encountered in several developing countries motivated, in the last few years, some microscopic modeling works, which proposed, using various approaches, models for heterogeneous and lane-less traffic; see for example [18], [19], where microscopic models for lane-less traffic are proposed, validated with real traffic data, and analyzed with respect to stability and other properties. Clearly, a major distinction to these modeling works is that they attempt to describe the driving behavior of real vehicles and drivers, while for TrafficFluid we need to design opportune movement strategies for safe and efficient CAV traffic flow.

Regarding nudging or, more generally, the possibility for vehicles to influence the driving behavior of other vehicles downstream, references are also sparse. While designing ACC regulators, Zhang *et al.* [20] proposed the idea of using not only sensor measurements for the front distance, as usual in ACC, but also rear sensor measurements to the vehicle behind, so as to improve the stability properties of the ACC system. Clearly, using measurements referring to the vehicle behind is an instance of downstream influence of that vehicle. This idea was taken over in several other ACC-design works [21], [22]. Despite reflecting influence from upstream, these works focus on lane-based longitudinal car-following stability issues and are therefore not directly relevant for our concept.

Macroscopic traffic flow theory started with the seminal works by Lighthill and Whitham [16] and Richards [23], was extensively developed in manifold directions [24], [25], and has been often applied for simulation [26] and control [1] purposes. The accumulated knowledge in this domain provides a solid and fruitful basis for further developments to address the novel characteristics of lane-free traffic and vehicle nudging. The lane-free traffic character may not need to give rise to structurally different macroscopic models, although model parameters (e.g., capacity) will certainly change. In contrast, the macroscopic impact of vehicle nudging must be reflected in corresponding structural extensions of conventional traffic flow models. Indeed, some elements related to vehicle nudging may be found in some earlier works in the literature [27], [28], where numerical simulations indicate that the application of forward forces may increase the road capacity and improve the stability properties of traffic flow. More targeted and rigorous recent investigations [29], [30] confirm the improved dynamic properties of traffic flow with nudging, and it is remarkable that the term "nudging" is being adopted in recent literature that investigates its macroscopic implications [31]. On the other hand, exclusive macroscopic considerations do not shed enough light on the microscopic vehicle-level implications of nudging for safety and convenience, and hence, they have to be complemented with microscopic vehicle movement strategies.

Another area that bears similarities with the proposed concept and has expanded enormously in the last decade is crowd modeling and simulation [32]–[34]. A similar area involving, beyond pedestrians, cyclists and vehicles is traffic modeling in shared spaces [35]. A popular approach, while modeling moving persons, is to apply potential fields (a concept stemming from robotics path planning [36]), called "social forces," around each person in the 2-D space. Social forces reflect a variety of possible person intentions and knowledge, infrastructure types, and constraints. One such social force is a repulsive force applied by a circular field around the center of each (circular) moving person. This repulsive force fades with distance from the person's center in the 2-D space and is included in the modeling to prevent collisions with other persons. In case two persons collide, that is, they touch each other, as, for example, in emergency or high-density situations, then special "pushing" forces apply, which act similarly as our nudging, albeit only in the case of adjacent colliding persons. Clearly, in the context of moving persons, uncontrolled physical nudging or pushing may have counterproductive implications. In summary, crowd modeling has some similarities with TrafficFluid, as it may contain instances of lane-free moving of persons along a bounded path, but it also has very significant differences: 1) it is a modeling approach aiming at mimicking real movements, not a design procedure for safe and efficient traffic flow and 2) it addresses situations quite different than high-speed vehicles driving on roads.

Finally, we note the existence of works referring to "artificial transportation systems" (see [37]), where, however, the term "artificial" reflects essentially a "simulated" transportation system, which represents and replaces the real system, while the term "artificial fluid" in this article is used literally and actively, reflecting the endeavor to design, deliberately and purposefully, an engineered traffic flow system.

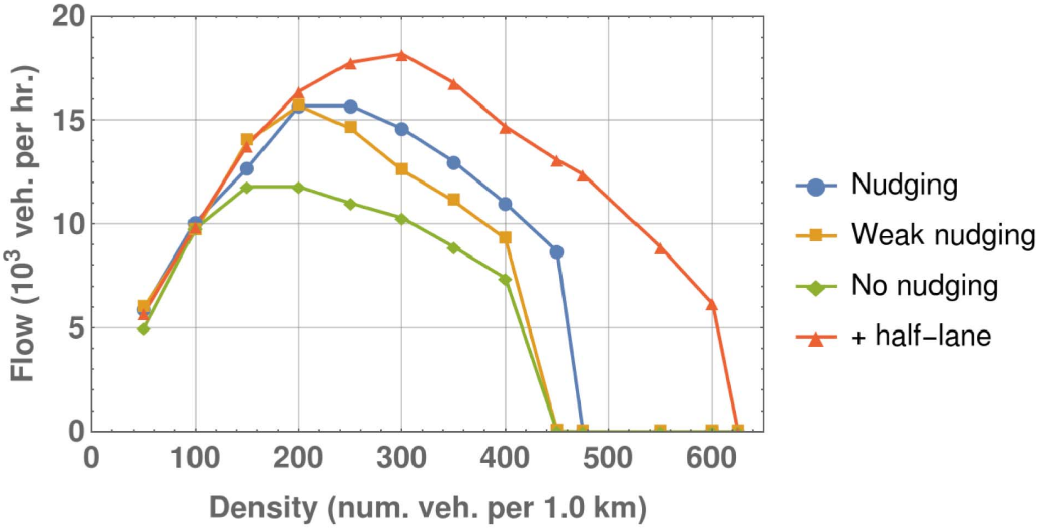

Fig. 4. *Emerging flow-density curves (fundamental diagrams) for various simulated scenarios.*

C. Developments Required

The proposed new concept calls for substantial investigations that are deemed necessary to understand implications and exploit opportunities toward conceiving a safe and efficient artificial fluid of traffic. We believe that such investigations must address, among others, the following challenging subjects:

1) vehicle movementstrategy design for various scenarios of connectivity (V2V and V2I); consideration of different vehicle types, including trucks, emergency vehicles, and manually driven vehicles; the possibilities and impact of forming vehicle platoons within the lane-free environment; the impact of incidents and congestion; consideration of various road infrastructures (motorways, arterials, road junctions) with laterally entering and exiting traffic and varying road boundaries; as well as development of realistic simulators;
2) emerging macroscopic traffic flow model development, whereby the models reflect the impact of vehicle movement strategies at the macroscopic level with respect to flow capacity, stability, and further stationary and dynamic features;
3) possible traffic-responsive (i.e., depending on the prevailing traffic conditions) actions, at the vehicle or traffic levels, including flexible capacity share among opposite directions.

In short, the proposed concept and related investigations address a novel traffic environment that must be designed from scratch. A solid background in terms of lane-based vehicle automation technology, conventional macroscopic traffic flow theory, and multifaceted traffic control measures and strategies facilitate the required new developments. We expect that new research by several groups will tackle some of the outlined, as well as additional arising issues, so as to explore the potential benefits of the new traffic paradigm, while addressing a major problem of modern society.

II. PRELIMINARY DEMONSTRATION RESULTS

For a quick demonstration of the TrafficFluid concept, an *ad hoc* strategy for the vehicle movement on a lane-free road was developed. The simulated vehicles are randomly selected from six prespecified vehicle-dimension classes and have desired speeds randomly selected from the range 25–35 m/s. All vehicles employ an identical movement strategy while driving on a circular road, whose 2-D surface has a length of 1 km and width of 10.2 m, which would barely suffice for three conventional motorway lanes. The vehicle movement strategy may be looked upon as an “artificial forces” approach, whereby the longitudinal and lateral forces determine the corresponding vehicle acceleration in two dimensions. There are three 2-D forces: first, the target-speed force depends on the deviation of the current vehicle speed from its desired speed; second, each vehicle generates repulsive forces, fading with distance, that are applied to vehicles behind it to avoid collisions; third, each vehicle generates nudging forces, fading with distance, that are applied to vehicles ahead of it. After calculating the accelerations, a bounding mechanism may clip them before they are actually applied so as to respect various technical restrictions, including the respect of the road boundaries.

To assess and demonstrate some features of the new concept, the outlined simulation environment was used in a number of experiments. Specifically, four series of simulations were carried out, each series being summarized in a corresponding stationary flow (veh/h) versus density (veh/km) diagram, which is known as the fundamental diagram (FD). Four FDs are displayed in Fig. 4: in the first one, nudging forces are switched off, while two more FDs were produced with weak and stronger nudging, respectively; finally, conditions on the fourth FD are identical as in the third, but the road width has been enlarged by 1.7 m, which corresponds to half-width of a conventional motorway lane. These summarized simulation results demonstrate that the following conditions hold.

1) In all cases, we obtain the characteristic inverse-U shape of a conventional FD.
2) Nudging increases the flows and the capacity.
3) The achieved flows and capacity without nudging are much higher than what is usually observed on a conventional three-lane motorway, something that is attributed mainly to the lane-free traffic character.
4) The incremental road widening (by half "lane") leads to further increase in flows and capacity. Remarkably, the observed capacity increase is roughly proportional to the increase in the road width.

The details of the movement control strategy and simulation are provided in [38].

III. CONCLUSION

This article proposes the TrafficFluid concept, which is a novel paradigm for vehicular traffic, applicable at high levels of vehicle automation and communication and high penetration rates, as expected to prevail in the not-too-far future. The concept relies on two principles: lane-free traffic and vehicle nudging. It is argued that lane-based traffic and the lack of downstream influence of traffic states (leading to the anisotropy property) are leftovers from the era of human driving, which should be abandoned in the era of CAV, as they reduce the traffic flow efficiency and safety. As CAVs are distinguished by superior capabilities, compared to human drivers, their movement may be designed so as to maximize efficiency of the emerging traffic flow, subject to safety constraints, but without the need to satisfy outdated constraints, such as lane-based driving and no influence from upstream. Since the vehicle movement is freed from such constraints and may be designed purposefully to lead to advantageous characteristics of the emerging traffic flow, the endeavor may be viewed as designing vehicular traffic flow as an artificial fluid.

Future research will focus on the design of safe, convenient, and efficient vehicle movement strategies by use of appropriate methods that have already been widely applied for lane-based CAV-movement design, stemming from automatic control, optimization, and AI. Furthermore, development of appropriate macroscopic models reflecting the emerging vehicular traffic flow is required in order to enable assessment of different movement designs at the traffic fluid level. Real-time traffic control measures and strategies may further enhance the traffic flow properties in response to the current traffic conditions. ■

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