Biologically Inspired Solutions to Fundamental Transportation Problems

O. K. Tonguz
Carnegie Mellon University, ECE Department, Pittsburgh, PA 15213-3890, USA
Email: tonguz@ece.cmu.edu

Abstract

Traffic congestion in urban areas is an acute problem which is getting worse with the increased urbanization of the world population. The existing approaches to increasing traffic flow in urban areas have proven inefficient as they are expensive and, therefore, not scalable. It is shown in this paper that a biologically inspired new approach could solve some of the fundamental transportation problems via a self-organizing traffic management paradigm.

I. INTRODUCTION

The urbanization of the world has intensified in the last two decades and probably more than half of the world population now lives in urban areas [1], [2]. The socio-economic reasons for this phenomenon are very clear: the impoverished masses in rural areas migrate to cities with the hope of employment and a better life. This trend is making the chronic problems of urban transportation even more acute as the capacity of existing road structure is far from being adequate to meet this increasing demand. In fact, the traffic congestion problem in urban areas is considered to be one of the “grand challenges” of our times awaiting scalable and cost-efficient solutions.

The published census data makes it clear that the existing infrastructure-based traffic lights are not scalable: e.g., in the U.S. less than 1% (only 260,000 intersections are equipped with traffic lights out of a total of 50,000,000 intersections in the U.S.) of all intersections are equipped with traffic lights [3], [4] even though several surveys have shown that the number of accidents at intersections equipped with traffic lights is 33% less than intersections with no traffic lights [5]. There are two major reasons for this: i) Cost — initial deployment cost of traffic lights at an intersection ranges from $50,000-200,000 depending on the complexity and sophistication of the traffic lights needed [6]. The electricity cost of
running a traffic light hovers around $3000 per year. Given that there are about 50 million intersections in the U.S., equipping all intersections with traffic lights could incur a tremendous cost (trillions of dollars); ii) Traffic volume — low volume of traffic at certain intersections might not warrant deploying traffic lights. Hence, despite major safety concerns (e.g., the World Health Organization disclosed that 1.27 million deaths were results of traffic accidents making them the ninth leading cause of death in 2009 [7]), infrastructure-based traffic lights have not proven to be scalable so far.

It is thus clear that a radically different new approach will be needed for a scalable and cost-effective solution to this longstanding problem. Given that intersections are responsible for maintaining the continuity of traffic flows in urban areas and the fact that most accidents happen at intersections, such a new approach might address the acute congestion problem in urban areas as well as increase the safety of driving.

In this paper, we argue that such a revolutionary approach exists and draws its inspiration from social insect colonies in nature such as ants, bees, and termites as well as other self-organizing biological systems, such as birds and fish [8]. This vision leverages the new vehicle-to-vehicle (V2V) communications capability of modern vehicles based on DSRC technology which allows the vehicles to communicate with each other and behave as a self-organizing network, very much like self-organizing biological systems [8]. We propose to migrate the infrastructure-based traffic lights to in-vehicle traffic lights which will enable cars to create "virtual traffic lights" at intersections and manage traffic without the use of infrastructure-based traffic lights. It is shown that this biologically inspired approach can increase traffic flow rates by about 60% during rush hours [9] which is pretty significant as such an improvement translates into reducing commute time of urban workers during rush hours, mitigating congestion, lessening carbon footprint of cars, increasing productivity, and supporting a greener environment.

II. INSPIRATION: SELF-ORGANIZATION IN BIOLOGICAL SYSTEMS

Carefully studying the behavior of several self-organizing systems in nature could shed light on how to solve some of the fundamental problems of transportation systems. While self-organizing systems include physical, chemical, and biological systems, in this paper our focus will be on self-organizing biological systems [8], [10]. The underlying mechanisms and the characteristics of self-organizing biological systems can be summarized (for details the interested reader is referred to [8]) as follows:
A. How Self-Organization Works

Many examples in nature indicate that positive feedback is a powerful mechanism for building structure in self-organizing biological systems. Negative feedback is the regulatory mechanism that keeps the process controllable. Negative feedback inhibits and shapes what could otherwise become an amorphous, overgrown structure. Hence, it is fair to say that positive feedback and negative feedback are the two essential mechanisms that create structure in self-organizing biological system. When an individual in a self-organizing system acquires and acts on information from: i) other individuals; ii) work in progress (stigmergy); or iii) the initial state of the environment, positive and negative feedback mechanisms get activated.

The transition from an amorphous state to a pattern is usually the result of applying a few simple rules at the local level and positive feedback. When large numbers of individuals act simultaneously, a new order or pattern emerges. Hence, the information needed for this new pattern is local as opposed to global and does not need to be coded at the behavioral level. Pattern formation in self-organizing biological systems therefore relies on positive feedback, negative feedback, and a dynamic system involving a large number of actions and interactions as opposed to a blueprint or recipe.

Environmental randomness can also affect which structures or patterns arise, thus enabling self-organization. The precise patterns that emerge are often the result of negative feedback provided by these random features of the environment and the physical constraints they impose, not by behaviors explicitly coded within the individual’s genome. Below, we elaborate on these mechanisms which are at the heart of self-organizing biological systems:

**Positive Feedback:** In most cases, positive feedback is the engine responsible for changes in a system. An initial change in a system is amplified and reinforced by positive feedback in the same direction as the initial deviation. Sometimes other terms such as self-enhancement, amplification, facilitation, and autocatalysis are also used to describe positive feedback.

**Negative Feedback:** The amplifying nature of positive feedback means that it has the potential to produce destructive explosions or implosions in any process where it plays a role. What keeps this in check? This is where negative feedback plays a critical role, providing regulation or inhibition to offset the amplification and helping to shape it into a particular stable pattern.

**How Organisms Acquire and Act upon Information:** The defining characteristic of self-organizing systems is that their organization arises entirely from multiple interactions among their components. In the case of animal groups, these internal interactions typically involve information transfers between
individuals. Information can flow within groups via two distinct mechanisms: signals (as in ant colonies) and cues (as in the case of deer trails).

**Information Obtained from One’s Neighbors:** In self-organizing biological systems the actions of individuals are not governed by a leader who tells everyone what to do. Instead, the most important information comes directly from an individual’s neighbors, often its nearest neighbors. In coordinating their movements in a school, fish use both positive and negative feedback mechanisms. Positive feedback helps thousands of fish to assemble into schools. Negative feedback regulates the specific spacing of fish within the school. A schooling fish that gets too close to a neighbor moves away to avoid a collision. Here again, the behavioral rule, ”Be most attracted to the largest group of fish”, provides positive feedback to create a cluster of individuals. At close range, negative feedback, ”if too close, move away” imposes shape and pattern on the cluster.

Members of a self-organized group often rely on simple behavioral rules of thumb to guide their action. This is because it is usually difficult, if not impossible, for an individual to obtain complete global information in a short period of time. These rules necessarily are often based upon local (hence incomplete) information, but this is generally sufficient. A member of a fish school does not need to know the long-range direction taken by the school or even the precise trajectories of all or any of its neighbors. It needs to only apply a few simple rules of thumb, such as these [8]:

1) Approach neighbors if neighbors are too far away;
2) Avoid collisions with nearby fish;
3) If the first two rules have been obeyed and neighbors are at the ”preferred” distance, then continue to move in the same direction.

**Information Gathered from Work in Progress (Stigmergy):** Information acquired directly from other individuals is not the only source of information used by self-organizing systems. In situations where many individuals contribute to a collective effort, such as colony of termites building a nest, stimuli provided by the emerging structure itself can be a rich source of information for the individual. In other words, information from the work-in-progress can promote and propel further activity.

B. Characteristics of Self-Organizing Systems

The main characteristics of self-organizing systems can be summarized as follows [8]:

**Self-Organizing Systems are Dynamic:** One of the most important characteristics of self-organizing systems is that such systems are *dynamic* and require continuous *interactions* among lower level components to produce and maintain structure.
**Self-Organizing Systems Exhibit Emergent Properties:** In most cases, self-organizing systems exhibit emergent properties. Such system-level properties cannot be understood as the simple addition of the individual contributions of the elements of the system as they arise from nonlinear interactions among a system’s components in non-obvious ways. Another interesting characteristic of self-organized system is bifurcations – a sudden transition from one pattern to another following even a small change in a parameter of the system. This is called ”tuning” a parameter in the system to induce a different pattern. A small change in a system parameter can result in a large change in the overall behavior of the system. Such properties could provide self-organized systems with adaptive, flexible responses to changing conditions in the environment and to changing needs of the system.

**Self-Organization Can Promote Stable Patterns:** Robustness and resilience are among the key characteristics of self-organizing systems which imply that they are stable over a wide range of parameter values. It appears that most biological systems operate in a parameter range far from bifurcation points and, therefore, stubbornly resist transition from one pattern to another. This is because most of the patterns are adaptive. Self-organizing systems often exhibit multi-stability, in which possible stable states, or attractors may occur. The final states attained by such systems usually depend on the initial conditions and the range of initial conditions that act as a basin of attraction for a particular attractor.

**Biological and Physical Parameters:** There are two types of parameters in self-organizing systems: biological parameters which are intrinsic to the organisms and physical parameters that arise from the environment or physical constraints. A parameter can affect the rules of thumb that determine the probability of performing a certain behavior under specified circumstances. Whether a self-organizing system implements a rule of thumb depends on information (about itself and the environment) that an organism acquires moment by moment, and on genetically encoded information that an organism possesses intrinsically.

**Role of Environmental Factors:** Environmental parameters may play a crucial role in shaping self-organized systems. The environment specifies some of the initial conditions, and positive feedback can amplify initial random fluctuations in the environment, and as a result the system may exhibit a number of different outcomes. A clear example is the raiding patterns of army ant colonies.

**Self-Organization and the Evolution of Pattern and Structure:** Fundamentally similar mechanisms may lead to very different patterns which seems counter-intuitive. More specifically, different patterns may result from the same mechanism operating in a different parameter range. As noticed by Charles Darwin, this points to the possibility that in evolution important changes in the properties of organisms and groups of organisms might result from slight changes in the tuning parameters of the underlying
Fig. 1. Two snapshots on the self-organizing behavior of a colony of ants: Fig. 1(a) shows the ants form a "living bridge" by using the members of their colony and the leaves in crossing a challenging area while Fig. 1(b) shows how the ant colony captures a formidable prey, namely a freshwater crab [11].

developmental systems.

**Simple Rules, Complex Patterns:** Most self-organizing systems, like biological systems in general, are highly complex and probably use multiple rules as opposed to a single rule. It is important to understand that simple nonlinear interactions between large number of individuals can lead to surprisingly complex patterns at the group level, patterns that are often unexpected even if detailed knowledge exists about the group’s members and their interactions.

As an example, it is remarkable that even though a human being has only about 100,000 different genes, the human immune system can generate antibodies against a nearly unlimited number (more than 100 million distinct antibody proteins) of foreign substances at a given time. Hence, each antibody protein cannot be mapped to a specific gene. This clearly shows that natural selection has led to a clever combinatorial scheme for reducing the information that needs to be genetically coded in the human immune system [8].

C. Example, Inspiration, and How to Apply it to Transportation Systems

As an example, Fig. 1 shows two snapshots of an ant colony extracted from a BBC video clip, now available on YouTube [11]. These two photos are very informative in showing how social insect colonies (such as ants, bees, termites, etc.) as well as other animal groups (such as birds and fish) can manage seemingly very complex functions by following simple local rules which lead to the desired emergent behavior at the global level.

More specifically, Fig. 1(a) shows how the ant colony in its need to cross an area uses the members...
of its colony and the existing leaves to form a "living bridge". In this way, the whole colony is able to overcome a major physical obstacle to their motion in a cooperative manner. This self-organizing behavior allows great flexibility in foraging as well as in moving the colony from point A to point B in order to protect the colony against attacks of other colonies or for other purposes (e.g., in retreating after a failed expedition for food). While the details are not clear, one can trace the role of positive feedback, negative feedback, information communicated by individual ants (presumably via pheromones), and even stigmergy in this example.

Fig. 1(b), on the other hand, shows a little later how the same ant colony captures an unexpected prey, namely a freshwater crab. This unexpected confrontation is very interesting and very informative for several reasons: it is well-known that ants are almost blind. In spite of this limitation, by using very simple local rules at the local level they are able to capture a formidable prey which seems invincible at a first sight (it should be mentioned that the shell of a freshwater crab is very thick and initially the ants are unsuccessful in penetrating into the crab – details can be seen from the video clip which is also available at http://www.ece.cmu.edu/~tonguz/main/materials). After the initial unsuccessful attacks, the ants notice that their prey’s most vulnerable parts are the joints which allow the crab to move around. Then, in a collective and cooperative manner the ants swarm to these vulnerable spots of the crab, infiltrate the crab from these joints, and tear away the soft white tissue which form the muscles of the crab. More specifically, the larger ants start slicing away the white tissue which makes the tear larger. This allows the smaller workers (ants) to infiltrate the crab and reach the muscle and the other softer tissue. At this instant [11] shows that the small and large ants at each joint of the freshwater crab are working in harmony and collaborating to reach their common goal. This collaboration seems to expedite the victory at each joint which, in turn, accelerates the capture of their prey. After this swarming continues in full force, in a very short period of time the confrontation is over: the ants “eat the crab inside out”.

Inspired by this example, and other self-organizing biological systems, in this paper we propose to use a new biologically inspired approach to solving the fundamental transportation problems we are currently facing. This vision is based on the new vehicle-to-vehicle (V2V) communications capability of modern cars which is expected to be a reality within a few years (by 2013). There is already a standard known as DSRC standard and allocated spectrum (about 75 MHz) for DSRC technology at 5.9 GHz.

These recent developments might allow vehicles to behave like social insect colonies, thus solving their conflicts and other problems in a collective and cooperative manner. As will be shown in the next sections, vehicles can communicate with each other at the most vulnerable or troublesome instances and/or locations and solve the ensuing conflicts or problems. More specifically, it is well-known that
intersections are one of the most critical elements of urban transportation systems in terms of safety and regulating the continuity of traffic flows. It is envisioned that by leveraging the V2V communication capability and by having in-vehicle traffic lights, self-organizing traffic control can be achieved whereby vehicles can "create" traffic lights by themselves at intersections whenever and wherever they need it which is in stark contrast to the current physical traffic lights paradigm which exists only at less than 1% of all the intersections in the U.S. This new vision is quite promising as it can revolutionize urban traffic management [12].

Just like the ant colony attacking the freshwater crab at its weakest or most vulnerable spots (joints in the limbs), the urban traffic can attack the congestion problems (maximizing traffic flows) at the most vulnerable spots which happen to be intersections. It will be shown in Section III that this is a powerful analogy.

During a typical afternoon rush hour, the initial motion of commuters could be considered as swarming and positive feedback since it starts slowly (say around 4 PM) and then gets amplified or peaks (say around 5 PM) as urban workers are anxious to go home after work (very much like ants initially attacking/swarming the freshwater crab). When the commuter vehicles enter the "network" (i.e., the city road structure), each vehicle tries to find an intersection and route that could minimize its travel time in traversing and exiting the "system". The existing road structure and the presence/absence of traffic lights act as the "environment" or "initial conditions" in shaping this flow. Each vehicle might change its route to destination depending on its view or knowledge of how crowded or congested each road segment is, opting for less crowded/congested alternatives. This is where negative feedback reshapes the traffic pattern in the "system". In addition to each driver's perception of how congested specific roads are, the proposed scheme allows different vehicles at intersections to obtain the most relevant and crucial information from their neighbors in establishing the right of way as opposed to a global leader telling all vehicles what to do. In this process, similar to ants at different joints of the freshwater crab, cluster leaders at intersections exchange and act upon relevant information in deciding who should act as the Virtual Traffic Light in managing the flow of vehicles at that intersection. Observe that the underlying mechanism in the information flow is sending and receiving signals similar to the case of ant colonies.

Furthermore, in the next section, simple rules for traffic management at intersections (local level) will be shown to lead to complex patterns at the global level (e.g., in a city) in terms of maximizing traffic flows. The emergent behavior (and the benefits) of Virtual Traffic Lights (VTL) scheme cannot be viewed as a simple addition of what happens at each individual intersection as the increase in flow rates is pervasive and valid for both low and high vehicle densities. Especially, at high densities (during rush
hours) the complex pattern and the benefit obtained is quite counter-intuitive. The dynamic characteristic of the proposed VTL scheme is clear as the new patterns generated is a result of multiple interactions at the local level (intersections) between cluster heads and also between members of each cluster. Such interactions are responsible for electing a leader which acts as a "virtual traffic light" and then dynamically hands this responsibility over to another leader. One can observe stable patterns and multistable regimes in the proposed VTL scheme as the benefit is very robust and it works well in low, medium, and high vehicle densities. Here, one can consider those densities as environmental or initial conditions. The details of the proposed solution are described in the next section.

III. PROPOSED SOLUTION

Traffic lights is a fundamental traffic control infrastructure that is currently used to govern traffic flow at intersections. It is well-known and well-understood that having physical traffic lights at an intersection can improve safety (33% less crashes at intersections equipped with traffic lights) and traffic flow with respect to intersections with no traffic lights. It is interesting to see that, despite these well-known advantages less than 1% of all intersections in the U.S. are equipped with traffic lights [3], [4]. It is an amazing statistic that even in NY city only about 24% of intersections have traffic lights [13]. There are two main reasons for this: 1) In some parts of cities or suburbs the volume of traffic is very low, thus making the use of traffic lights a luxury; 2) Cost of deploying and maintaining traffic lights. It has been reported that the initial deployment cost of traffic lights at an intersection could vary between $50,000-200,000, depending on the complexity and sophistication of the traffic lights used [6]. The operational cost of running traffic lights at an intersection varies between $2000-3000/year. These two reasons and especially the cost explain why traffic lights do not exist at every intersection despite the aforementioned advantages. In this paper, we propose to solve this major scalability issue for ubiquitous traffic control by migrating the traffic lights into cars and leveraging the emerging vehicle-to-vehicle communications paradigm. The envisioned scenario is shown (in animated fashion) in Fig. 2.

This vision illustrated in Fig. 2 can facilitate having traffic lights when one needs them and wherever one needs them. In other words, ubiquitous traffic control becomes possible. This, in turn, can solve some of the fundamental transportation problems currently being faced, especially in urban areas, such as mitigating congestion, reducing the commute time of urban workers during rush hours, lessening the carbon footprint of cars, increasing productivity, and supporting a greener environment.
A. Main Concept

With the advent of VANET and V2V communication, traffic lights could migrate from being an infrastructure of the road to a cyber-physical infrastructure represented inside the vehicle. A fully distributed protocol based on inter-vehicle communication could create "virtual traffic lights" (VTL). At the core of this distributed protocol is the election of a leader at an intersection who will perform the functionality of traffic lights based on the consensus reached between cluster leaders of each leg of the intersection using V2V communications. Fig. 3 illustrates the leader election concept.

The principle of operation of the proposed scheme is relatively simple, as shown in Fig. 3. Through
a dedicated Application Unit (AU) which maintains an internal database about intersections, when approaching an intersection each car checks whether there is an established virtual traffic light or if there is a need to create one. If there is a VTL already, the other cars obey the existing VTL as passive nodes. If there is no VTL and a crossing conflict is detected, the cluster leaders in each leg of the intersection must communicate to establish a leader who will undertake the role of a virtual infrastructure and manage the traffic at intersections. Once this leader is elected, all the other cars at that intersection obey the instructions of the leader. More specifically, the leader must have two important characteristics:

1) It should present itself and the cars in its cluster and in the same direction the red light while presenting the green light to the orthogonal direction.

2) It should be the closest car to the intersection in its own cluster (i.e., be the cluster leader) for improving the RF propagation and broadcast capabilities of the VTL messages to all approaches.

The leader election process can be based solely on the location table maintained at each car (node). The location table allows each node to compute, for each road, the closest vehicle to the center of the intersection (i.e., cluster head). Based again on the location table, the lane-level topology map, vehicles heading, speed and lane determination, the cluster heads can determine the most imminent conflicts. By choosing among the cluster heads, the farthest one from the intersection, one can ensure that the elected leader will have enough time to stop at the intersection and function as VTL. The leader election process requires an acknowledgment of the elected leader by all other cluster heads.

The criteria for deciding which approach/direction should have “the right of way” could be based on several different considerations. However, in this paper, the elected leader is assumed to make this decision based on the number of cars in each cluster and some fairness considerations so that no direction/approach is penalized in an unfair manner (details of the VTL protocol and the leader election algorithm can be found in [12]).

B. Key Results

To see the impact of the proposed scheme, traffic in the city of Porto in Portugal was simulated via a large-scale simulator known as DIVERT. Porto is the 2nd largest city in Portugal with a population of about 1 million people.

DIVERT is a large-scale simulator that allows for micro-simulation of more than 20,000 cars with a high degree of realism. It includes a complex editor of traffic entities, allowing use of road segments at the lane-level, describing detailed connectivity at intersections, traffic lights interplay, and several individual parameters that affect the behavior of drivers (e.g., aggressiveness, braking and acceleration patterns,
Fig. 4. The envisioned in-vehicle traffic lights concept: Observe that the in-vehicle traffic lights are on the windshield of the car so that the driver can easily see what to do. Such in-vehicle traffic lights will be interfaced with the DSRC radio in the car.

Fig. 5. The DIVERT simulator with the user interface is shown in Fig. 5(a) while the map of the city of Porto is shown in Fig. 5(b) where the red dots indicate the intersections which are equipped with traffic lights [9].

patience threshold). DIVERT mobility model has been validated against empirical data collected through a recently conducted comprehensive stereoscopic aerial survey [14].

The impact of VTL was evaluated in two separate scenarios using the DIVERT simulator: 1) In a 10x10 Manhattan Street topology where the block size was assumed to be 125 m; 2) In the entire city of Porto in Portugal which comprises 965 km of road structure and 2000 intersections out of which 328 are equipped with traffic lights. This corresponds to a percentage of 16% of all intersections being equipped with traffic lights. The map of the city of Porto is shown in Fig. 5(b).

The Manhattan Street topology was studied for two different scenarios: i) A scenario which assumes all intersections are equipped with traffic lights (see Fig. 6(a)); ii) A scenario whereby only 16% of intersections are equipped with traffic lights (see Fig. 6(b)). Observe that the Manhattan and Porto scenarios are very different: the Manhattan Street topology corresponds to a downtown area which is
The increase in average traffic flows with the proposed scheme for 10x10 Manhattan Street topology. While Fig. 6(a) shows the expected benefit compared to a 10x10 Manhattan Street scenario with traffic lights at every intersection, Fig. 6(b) shows the expected benefit for a Manhattan Street scenario where only 16% of intersections are equipped with traffic lights.

Results for the 10x10 Manhattan Street topology are shown in Fig. 6 with 95% confidence intervals. The results are averaged over 14 runs for each density in each scenario. Results in Fig. 6 show the substantial benefits of the proposed scheme. While in Fig. 6(a) (the case where all intersections are assumed to be equipped with traffic lights) the increase in average flow rates ranges from 70%-20% going from low densities to medium-high densities, in Fig. 6(b) the proposed scheme can increase average flow rates from 20% to 60%, going from low densities to high densities. The results in Fig. 6(a) confirm intuition since at high densities the utilization of intersections with fully equipped traffic lights cannot be further improved as it is already close to 100% of the capacity. Fig. 6(b), on the other hand, shows that in a city where only 16% of the intersections are equipped with traffic lights, the proposed scheme can increase average flow rates by 60% during rush hours which seems pretty significant.

Because the results of Fig. 6 was for an ideal Manhattan Street topology, it is not clear whether the same type of benefits can be expected from a real city where the topology is not Manhattan-Street and the road structures are not ideal with very different intersections (5-way junctions, T-junctions, Y-junctions,
etc.), roundabouts, etc. are quite common in a typical city.

Fig. 7 shows the results of a large-scale implementation of the proposed VTL scheme in the city of Porto which is the 2nd largest city of Portugal. Indeed, the road structure of Porto is very different from an ideal Manhattan Street topology with a huge roundabout in the downtown area, a major highway running through the center of the city, different types of intersections (with 3, 4, or 5 legs), etc.

Observe that, the proposed scheme again leads to about 60% increase in average flow rates in Porto at high vehicle densities (i.e., during rush hours) which is somewhat consistent with the Manhattan Street results. Such an increase in average flow rates seems very significant for several reasons.

C. Implications

The biologically inspired solution proposed for traffic management seems very promising as it can increase average traffic flow rates by 60% during rush hours. The envisioned new scheme has serious implications and significant benefits which go far beyond the realm of transportation problems. The proposed scheme can:

1) make traffic control at intersections ubiquitous which in turn can substantially reduce the number of accidents at intersections (especially at intersections that currently do not have traffic lights);
2) reduce the commute times of urban workers significantly during rush hours;
3) mitigate congestion;
4) increase productivity of a nation;
5) lessen the carbon footprint of vehicles;
6) eliminate the huge deployment and maintenance cost of traffic lights by migrating traffic lights into vehicles;
7) support a greener environment by abolishing the need for external infrastructure-based traffic lights;
8) accelerate the ongoing initiative in autonomous driving as crossing intersections is probably the most challenging component of autonomous driving.

D. Open Research Problems

While the herein outlined biologically inspired Virtual Traffic Lights scheme can revolutionize future traffic management, much work needs to be done before the large scale deployment of this scheme. Below, we briefly discuss some of these issues.

The success of the proposed approach can be accelerated by the adoption of the DSRC technology at the federal level and by making it a mandate for car manufacturers. The role of public policy decisions
at the federal level and the corresponding legislation will thus be critical for accelerating the realization of the vision outlined in this paper. It is encouraging to see that the U.S. Department of Transportation (DoT), as well as the DoTs of some other countries, is moving in this direction.

At the technical level, there are several challenges that need to be carefully addressed: The leader election algorithm described in Section IV has to be made fail-safe so that the RF propagation challenges due to the existing buildings and/or other obstructions do not lead to malfunctioning of the protocol as this might cause accidents.

Similarly, malicious security attacks (such as jamming attacks or other forms of cyber attacks) should also be considered and the necessary mechanisms should be designed to make the operation of the proposed scheme provably secure and fail-safe.

Another technical challenge is how to incorporate the presence of pedestrians and cyclists in the proposed scheme. One way to do this might be to integrate this possibility into the design of the VTL scheme so that the cycle duration and green split of the proposed scheme is cognizant of this possibility. Another possibility might be to put external lights on the exterior of a car (e.g., on the outside mirrors) which show to pedestrians and cyclists the current state of intra-car traffic lights shown to the driver inside the car.

Other technical challenges include how to incorporate the rules enforced by traffic management institutions in cities (such as the City Hall or the Local Government authorities) into the proposed scheme. In certain cities, for example, the access of cars to the downtown area might be intentionally restricted to give pedestrians and cyclists a more pleasant walking or biking experience in those areas. Such rules could easily be integrated into the design of the proposed VTL scheme.

IV. RELATED WORK

Many researchers in the last forty years have noticed that intersections and their control via infrastructure-based traffic lights can be approached as an optimization problem. This includes efforts and proposals for making traffic lights adaptive, adaptively changing the cycle duration and/or green split ratio of traffic lights [15], [16], [17], [18]. SCATS and SCOOT, for example, are well-known systems that are currently used in commercial systems. In addition, Dynamic Programming and Reinforcement Learning based approaches have also been proposed [18], [19].

While these approaches have certainly improved urban traffic management, their impact is limited as they are not scalable. It is also important to note here that none of these approaches are based on using
Vehicle density (veh/km²)

% benefit

Expected benefit when compared to 16% TL in Porto

Fig. 7. The increase in average traffic flows with the proposed scheme for Porto. The percentage benefit is with respect to the existing traffic management scheme which has 16% of intersections in Porto equipped with traffic lights. While in this figure the benefit is quantified as the percentage increase in traffic flows as a function of vehicle density, one could also quantify the benefit of the proposed scheme in terms of the percentage decrease in average commute time in a given city as a function of the total number of commuter vehicles during rush hours.

in-vehicle traffic lights in conjunction with V2V communications of cars approaching intersections for determining the “right of way” at intersections which is the approach proposed in this paper.

V. Conclusion

Over millions of years, biological systems have survived and sustained themselves in a self-organizing manner. Social insect colonies (such as ants, bees, and termites) provide compelling examples of self-organizing biological systems which can find food (foraging), protect themselves from predators, and adapt to changing environmental conditions in a seamless and dynamic manner. It is this resilience that kept these species alive and helped them to thrive.

In this paper, inspired by self-organizing biological systems (ants, bees, termites, fish, birds, etc.), we propose to solve some of the fundamental transportation problems by designing intelligent local rules for vehicles approaching intersections, which are considered to be the most critical, vulnerable and troublesome components of urban transportation. More specifically, we propose to replace infrastructure-based traffic lights with in-vehicle traffic lights which can form a “virtual traffic light” whenever and wherever needed. The premise of this proposal is the emerging V2V communications capability of contemporary vehicles using the DSRC technology. It is shown that the proposed approach can achieve ubiquitous traffic control in a self-organized manner, similar to social insect colonies. This ubiquitous traffic control can lead to more than 60% increase in average traffic flows which seems pretty significant.
This benefit has serious implications in terms of reducing the commute time of urban workers, mitigating congestion, increasing productivity, lessening carbon footprint of cars, and even supporting a greener environment.

The radical vision outlined in this paper seems very timely as urban transportation and environmental problems are getting worse with time. The success of the outlined vision can be accelerated if engineers and scientists from different disciplines (transportation, engineering, computer science, physics, biology, operations research, etc.) work on different pieces of this puzzle as the required expertise to solve these problems appear to be quite broad and inter-disciplinary. Can we make urban traffic manage itself like ant colonies or other self-organizing biological systems? Time will tell but the case for it seems compelling.

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**Biographies**

Ozan K. Tonguz (tonguz@ece.cmu.edu) is a tenured full professor in the Electrical and Computer Engineering Department of Carnegie Mellon University (CMU), Pittsburgh, Pennsylvania. He currently leads substantial research efforts at CMU in the broad areas of telecommunications and networking. He has published about 300 papers in IEEE journals and conference proceedings in the areas of wireless networking, optical communications, and computer networks. He is the author (with G. Ferrari) of the book Ad Hoc Wireless Networks: A Communication-Theoretic Perspective (Wiley, 2006). He co-founded Virtual Traffic Lights (VTL), LLC, a CMU spinoff, in December 2010, which specializes in providing solutions to several transportation problems, such as safety and traffic information systems, using V2V and V2I communications paradigms. His current research interests include vehicular ad hoc networks, wireless ad hoc and sensor networks, self-organizing networks, bioinformatics, and security. He currently serves or has served as a consultant or expert for several companies, major law firms, and government agencies in the United States, Europe, and Asia.