Societal Intelligence for Safer and Smarter Transportation

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***Abstract*—Recent years have witnessed exciting developments in our transportation system with increasingly intelligent vehicles and infrastructure. The transportation system is envisioned to be highly heterogeneous, consisting of diverse participants with mixed intelligence and connectivity. Among them, autonomous vehicles have the highest intelligence and connectivity level and could contribute greatly to the operation of the transportation system in an efficient and reliable manner. However, the current design of autonomous driving techniques is mostly concerned with the autonomous vehicle at the individual level, and the overall transportation system does not provide proactive support to autonomous driving. In fact, the increasing intelligence and connectivity in transportation could be leveraged to significantly enhance the safety and efficiency of individual vehicles and the entire system. To facilitate this, vehicles need to interact and cooperate both among themselves and with the transportation infrastructure and management. In this article, we propose the societal intelligence (SI) framework. Different from the existing multientity intelligence frameworks, SI allows for much diverse interactions among the multiple entities at different levels and is thus suitable for transportation. In addition, we also render the driving process into four functional layers and demonstrate how the social intelligence framework can adapt to these layers, respectively.**

***Index Terms*—Connected autonomous vehicles, intelligent transportation systems (ITS), Internet of Vehicles (IoV), societal intelligence (SI).**

I. INTRODUCTION

RECENT years have witnessed exciting developments in our transportation systems. On the one hand, intelligent capabilities are introduced into various system components at different levels, including the infrastructure and the vehicular participants in transportation, inaugurating the era of intelligent transportation systems (ITS) (see [1]–[5]). On the other hand, connectivity is introduced to allow information sharing and collaborations among the participants in the system with the Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-Everything (V2X) communications, and Internet of Vehicles (IoV) networking (see [6]–[12]). With the intelligence distributed across the entire system and the connectivity linking major elements, the ITS is evolving toward automated and global control. The safety of the entire system is expected to be improved and the system evolves in a more healthy manner. Both the efficiency and reliability of the transportation system will be improved.

Among the new elements and techniques in ITS, autonomous driving stands out [13], [14]. The autonomous vehicles have the full intelligent capability and are expected to drive effectively and safely without any human interventions. Introducing the autonomous vehicles into our current transportation system has many benefits, such as enhanced safety, alleviated congestion, improved parking conditions, more efficient utilization of transportation resource, better commuting experiences, and so on [15]–[17]. Although the research on driverless vehicles dates back to the 1920s and the first prototype of autonomous vehicles dates back to the 1980s. They are not attracting people's attention until a little more than a decade ago due to the limited hardware technology. The past decade has witnessed leaping improvements on many supporting techniques, such as sensing technology, high-performance computing, artificial intelligence, computer vision, wireless communications and networkings, and so on. These bring a promising future for driverless autonomous vehicles. The realization of autonomous vehicles and its common adoption in people's daily life has been put on the agenda. Nowadays, many research institutes and companies over the world have already put the driverless autonomous vehicles into road tests, even public roads. In the United States, many states are giving permission to allow autonomous vehicles to drive in their public transportation system and many companies, such as Uber, Google, etc., are putting their driverless cars into operations (see [18]–[20]).

However, some recent accidents involving autonomous vehicles raised the public's concerns on the readiness of the technology and questions about whether the many advantages of the autonomous vehicles can be capitalized in the near future (see [21]–[23]). Over the years, efforts on autonomous vehicles have been mostly made to improve the autonomous

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vehicle's individual intelligence level. However, when a vehicle operates in an isolated manner, no matter how mature the intelligent level is designed to be, the vehicle's perception range is limited and hence its driving strategies would be developed based upon a very local perspective without a global view. The bottleneck imposed by a vehicle's limitation in terms of both space and time cannot be overcome by simply improving its intelligence level. Fortunately, with recent developments in the communications and networking technologies in ITS, connectivity is provided to autonomous vehicles to share information and cooperate with other vehicles and the ITS infrastructure. As a result, autonomous vehicles can operate with a global view.

The introduction of cooperation can not only improve the efficiency and reliability of the operation of autonomous vehicles themselves but also enables the autonomous vehicles to contribute to the operation of the entire transportation system. The autonomous vehicles are distributed across the entire transportation system. On the one hand, they could act as valuable sensors to provide information about the working conditions of the entire ITS. On the other hand, they can act as actuators to take actions to impose influences on other vehicles or traffic participants as desired by the ITS control center and facilitate the healthy evolution of the entire transportation system.

While the introduction of cooperation to autonomous vehicles might bring in many potential benefits, there lacks a framework guiding and governing the entire cooperation process. Though there are several existing multientity intelligence frameworks that describe the implementation of intelligence with cooperation among multiple participants, none of them could capture the unique features for the cooperation among autonomous vehicles. Specifically, in the existing frameworks, entities operate without any self-interest and the only concern is the overall system performance. However, for autonomous vehicles in ITS, each of them operates with its own tasks and self-interests. While they would be willing to contribute to the wellness of the entire transportation system and for most of the time, the cooperation brings in a win–win situation for the collaborating autonomous vehicles and the entire transportation system, the autonomous vehicles do not lose track of their own interests and would be unwilling to make self-sacrifices. To capture this perspective for their collaborative efforts in intelligence, in this article, we propose a brand new intelligence framework involving cooperation among different entities, namely, the societal intelligence (SI) framework. For this framework, we also address the functional and supporting modules for the implementation of the SI framework for autonomous vehicles in ITS.

The remainder of this article is organized as follows. In Section II, we introduce the main participants in transportation with mixed autonomy and/or connectivity. In Section III, we review different multientity frameworks that describe intelligence with the cooperation and analyze their feasibility for transportation applications. In Section IV, we propose the SI framework and discuss its distinct features. In Section V, we demonstrate the SI application to transportation systems with intelligent vehicles. Concluding remarks are presented in Section VI.

II. TRANSPORTATION OBJECTIVES AND PARTICIPANTS

The overall objective of the transportation system is to transport someone or something from one place to another safely and efficiently. While safety is shared among individual vehicles and the overall transportation system, efficiency can have very different meanings from their respective perspectives.

For individual vehicles, driving decisions are typically made based on the time efficiency, fuel efficiency, and sometimes toll efficiency, subject to the presumption that the driving process is safe. The driving decisions are multilateral, ranging from relatively more global ones, such as when to make the trip and which route to take, to relatively more local ones, such as traveling speed, lane switching, passing, fueling or charging, parking, etc.

In the meantime, the overall transportation system is more concerned with road utilization efficiency, congestion reduction, pollution control, and road condition maintenance. The transportation planning and management can take corresponding actions in order to achieve these objectives. Similar to individual vehicle actions, the system-level actions can also be categorized into relatively more global ones, such as road planning and transportation regulations, and relatively more local ones, such as real-time transportation intervention via dynamic road/lane traffic control, dynamic tolling, etc.

It is clearly impossible that the objectives of the overall transportation system are perfectly aligned with those of individual vehicles. In fact, one may at times even find those contradicting each other. Nevertheless, as vehicles are the main players in the road transportation system, these objectives inevitably interweave and interact. For instance, road planning and transportation regulations are designed based on the aggregated behavior of individual vehicle driving decisions, and the real-time transportation intervention can only take effect when individual vehicles respond accordingly. Of course, transportation planning and management actions can also significantly influence individual driving decisions.

With the recent development and the introduction of various new elements and vehicular technologies, including autonomous driving, our transportation system has evolved into a complex dynamic system with diverse entities, as illustrated in Fig. 1. To first understand and then optimize the operation of the entire system, it is necessary to review the various participants in the transportation system, in terms of their respective features and interactions with the overall transportation system.

A. Traditional Vehicles

Traditional vehicles are human-operated vehicles. In terms of the environment perception and situational interpretation, the human drivers are naturally limited by the vision range. Without information sharing with other vehicles and the infrastructure, their driving decisions and actions are based upon very local situational awareness, and driven by individual

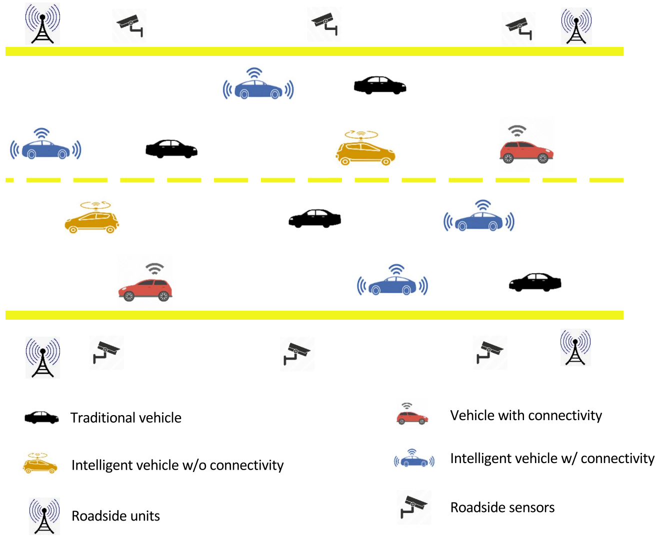

Fig. 1. Illustration of the intelligent transportation system with diverse participants.

driver's sole interest in terms of safety, time efficiency, and cost (fuel and toll) efficiency.

Without constant connectivity to other participants in transportation through which they can actively share information, the status and driving intentions of traditional vehicles can only be sensed, tracked, and possibly predicted by the transportation infrastructure and neighboring vehicles with machine intelligence. Evidently, such inferences come with a wide range of uncertainty. As a result, traditional vehicles are mainly passive and selfish participants of the transportation system. They cannot be remotely intervened by the transportation management but can be influenced by connected/intelligent vehicles locally.

B. Intelligent Vehicles

Newer vehicles are commonly equipped with intelligence, which could be categorized into the five levels of autonomous driving [24], with 5 being the highest level. In general, intelligent vehicles can, to various extent, actively sense the environment, interpret the driving situation, and make corresponding decisions to accomplish their driving tasks based upon their perception of the transportation system operating condition. This process consists of two key components, namely: 1) acquiring situational awareness and 2) making driving decisions.

In terms of the first component, even the most advanced intelligent vehicles today are gaining situational awareness mainly based on various sensors onboard individual vehicles. This approach not only incurs high cost but also imposes a limited sensing range similar to traditional human-operated vehicles. Given the limited scope of situational awareness, today's intelligent vehicles can only make driving decisions that are local in both space and time.

In terms of the second component, lower level autonomous vehicles that deploy intelligence to enhance human driving, two models are typically adopted: 1) driver behavior analysis, in which the status of the human driver is constantly monitored while warning signals are provided when driver behavior abnormality, such as fatigue, drunkenness, lack of focus, etc., is detected and 2) driver assistant units, which provide environment information to the driver to assist the driving and ensure safety, such as tailgating detection, blind-spot detection, etc. More advanced intelligent vehicles tend to follow artificial intelligence-empowered algorithms. These algorithms are repeatable given the environmental parameters. Hence, it is possible for driving decisions to be simultaneously derived or simulated at the transportation control center. When this is pursued for a reasonable percentage of all vehicles, the transportation control center can potentially take into account the interactions among vehicles to very fine granularity. It is also possible to develop mechanisms by which personalized transportation control interventions can be adopted at individual intelligent vehicles. Consequently, unlike traditional vehicles, intelligent vehicles have great potential of integrating system-level safety and efficiency considerations into selfish individual vehicle concerns such that solutions that are preferable from both perspectives can be reached.

C. Connected Vehicles

With the rapid development of V2X communications and their increasing deployment in the transportation system, real-time and extensive information exchanges can take place among autonomous vehicles, as well as the infrastructure and other networked road participants.

Once connected, both traditional and intelligent vehicles can actively share and report their driving intentions and decisions. The intelligent vehicles can also share their sensed environment or driver status with neighboring vehicles and the ITS infrastructure. In the meantime, the transportation management center can also send the aggregated and processed traffic status information or intervention messages to any connected vehicles. Such information can be integrated into the driving decisions for intelligent vehicles, or used to assist human driver decisions for traditional vehicles.

D. Transportation Infrastructure

In the transportation system, there are traditional facilities, such as roads, traffic signs, roadside posts, etc., as well as recently introduced intelligent units, such as the roadside units (RSUs) for advanced sensing and communications, the traffic monitoring center, the traffic control center, etc. With increasing intelligence and connectivity, the transportation infrastructure will be capable of monitoring the operating state of the entire transportation system, such as road utilization efficiency, traffic flow rate of various road segments, and road congestion and safety. When needed, the transportation infrastructure could also intervene behavior of various transportation participants for improved safety and efficiency. For example, dynamic need-based traffic flow control could be initiated at the entrance of a highway to reduce the road congestion level during rush hours, and dynamic toll could be implemented for certain road segments at different time of

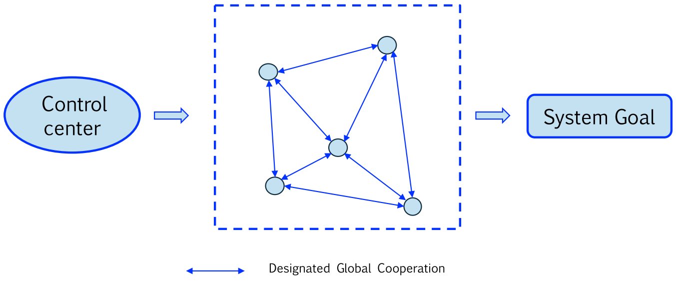

Fig. 2. Illustration of the elements and interactions in a collective intelligence system.

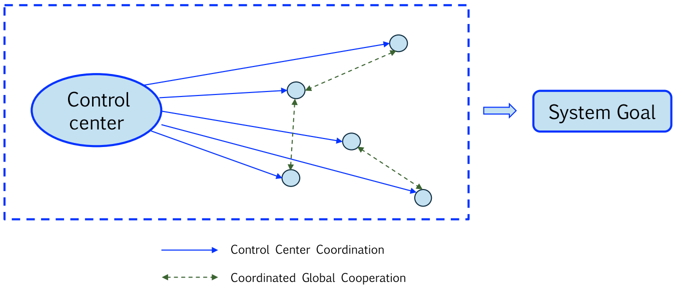

Fig. 3. Illustration of the elements and interactions in a collaborative intelligence system.

the day. With increasing intelligence and connectivity on individual vehicles, it is expected that more direct intervention would be possible, where the transportation management center sends personalized traffic advices to individual vehicles. In addition, the transportation infrastructure is also expected to be linked with the electric charging infrastructure so that the transportation and energy can be jointly planned, operated, and optimized.

III. MULTI-ENTITY INTELLIGENCE

As discussed in the preceding section, the transportation system and its participants all need to achieve their respective safety and efficiency objectives. With the penetrating deployment of intelligence and connectivity among the transportation participants, it is natural to explore the possibility of exploiting multientity intelligence in transportation. In the existing literature, there are several technologies along this line. We will next introduce those and discuss their feasibility for transportation.

A. Collective Intelligence

Also known as "swarm intelligence," collective intelligence is used to describe the collaborative efforts of the intelligent evolution for a group (see [25], [26]). Under this framework, all entities in a group work together collectively on a group task toward one or more global objectives. Individuals are anonymous with no personal interest, preference, or objective. The entire group tries to reach some consensus. In other words, the collective intelligence is a homogeneous process. The main interaction between the intelligent entities within this frame is the *designated global cooperation* with predefined rules given by the system control center. An example of collective intelligence is the cooperation of unmanned aerial vehicles (UAVs) to accomplish a task as a group (see [27], [28]). The performance of collective intelligence is measured by the group task completion. Individual UAVs follow the predefined collaboration protocol to accomplish the task together. So long as it is beneficial to accomplish the system goal, it does not matter which entities contribute more than others, which ones are more intelligently developed during the evolutional process, or which ones take more essential roles in accomplishing the system task. Under extreme conditions, even the survival of individuals is dispensable if needed by the group. An illustration of the elements and interactions in a collective intelligence system is shown in Fig. 2.

B. Collaborative Intelligence

Collaborative intelligence is sometimes used interchangeably with the term "collective intelligence." However, there are some subtle yet essential differences between the two. Specifically, entities participating in the collaborative intelligence framework do not have to be anonymous (see [29], [30]). In other words, each individual can have its distinct features and intelligence level, and there is typically some extent of heterogeneity among the participants: some could be stronger while some weaker; some might contribute more while some less. Nevertheless, similar to collective intelligence, the ultimate goal is still to accomplish some group tasks. Individuals do not have their selfish interests or objectives. The interactions among individual intelligent entities could be characterized by *coordinated global cooperation* under the system control center. An example is crowdsourcing, where the system solicits information from a group of users about some specific event and all users contribute their collected information according to their individual (and often heterogeneous) capability (see [31], [32]). Under this framework, the participants might have different capabilities to contribute to the overall system under different situations and the system center monitors the status of each individual entity and coordinates the cooperation among them in order to improve the overall system efficiency. All entities have the same incentive to contribute to the overall system and always follow the commands from the system control center without any reservation. An illustration of the elements and interactions in a collaborative intelligence system is shown in Fig. 3.

C. Feasibility for Transportation

Evidently, existing multientity intelligence frameworks involve only objectives and tasks for the group. Although individual capabilities, functionalities, and locality of participants can be addressed to the various extent in these frameworks, the participating entities' individual preferences, interests, and objectives are completely neglected.

In transportation systems, the situation is drastically different. The ultimate goal of transportation is to best meet the safety and efficiency objectives of individual transportation participants. Although the participants can jointly take actions to help achieve the system-level safety and efficiency objectives of transportation, these are actually meant to enhance the system support to the participants. In other words, the individual objectives are primary in transportation, while the system objectives are secondary and supportive. As a result, none of the existing multientity intelligence framework fits the needs of our evolving transportation system.

IV. SOCIETAL INTELLIGENCE FOR TRANSPORTATION

As we discussed, individual objectives are primary in transportation. However, achieving these individual objectives involve extensive interactions among all transportation participants as well as the infrastructure. Traditionally, the interactions among individual transportation participants are mainly competitive in nature, especially for travel efficiency considerations. The competitions are with respect to limited resources, such as highway lanes, right to the road, cheaper, faster, or more conveniently accessible fuel stations, etc. Note that such competitive interactions have never existed in the present multientity frameworks overviewed in Section III. Another aspect of these interactions is cooperation, though rather suitable and implicit in traditional transportation. Only via cooperation among individual transportation participants, travel safety can be ensured. These cooperations occur both at the individual participant level, such as checking and sometimes slowing down to yield on multilane roads, and at the system level, such as imposing traffic lights, stop/yield signs, and laws and regulations. With the increasing intelligence and connectivity at all levels, it is envisioned that such interactions and interventions are to be taken to a different level both in quality and quantity. These extensive and complicated competitive and cooperative, voluntary and regulatory interactions and interventions, both among individual participants and the system (see [33]–[37]), call for a new paradigm of the multientity intelligence framework. Based on the resemblance of the interactions and interventions in transportation with those in the human society, we propose an SI framework to model, analyze, and optimize the transportation system.

A. Interactions Under Societal Intelligence

Main interactions in the SI framework include local cooperation, local competition, global cooperation, regulatory intervention, and personalized intervention. Next, we will discuss each of these interactions in the context of transportation. In the transportation system, the individual participants have two main functions, namely: 1) establishing situational awareness and 2) making driving decisions that fit the environment. Both of these functions are typically local. The system-level functions include assisting individual participants to establish more useful and larger range situational awareness, and providing participants with regulatory or personalized driving advices. These are relatively global and can have an impact on the safety and efficiency of both the individual participants and the system overall.

1) *Negotiated Local Cooperation (NLC):* While all road participants have their own self-interests, they are closely coupled together since they are sharing the same environments and transportation resources, and the actions of each of them can affect each other. With this relationship, at the local level, the intelligent vehicles could potentially cooperate with each other for their mutual benefits for multiple applications and with different features. Whenever it is possible for a group of vehicles to take actions to benefit all players in the group, NLC can be initiated. First, the intelligent vehicles can cooperate with each other to acquire better situational awareness. For vehicles operating in an isolated manner, the situational awareness heavily relies upon onboard sensors and greatly limited by the physical position of the vehicle itself, leading to very local situational awareness in both space and time. With the local cooperation among connected vehicles, they can exchange direct information about themselves. As a result, sensing would no longer be the sole means to detect and track those vehicles. Even if the vehicles are beyond the sensing range, one can still obtain the situational awareness on them. If an object is indeed within the sensing range, then the information provided by the onboard sensors can further improve the precision and accuracy of the tracking information about this object (see [38]–[41]). At the same time, vehicles and other objects without connectivity would be cooperatively sensed by intelligent vehicles. Cooperative sensing benefits the situational awareness in two aspects: 1) extend the sensing range and avoid blind spots, achieving beyond-the-vision-range situational awareness and 2) provide redundancy in sensing for the overlapped sensing regions across multiple vehicles, and hence improve the accuracy and robustness of sensing. Second, at the decision level, the intelligent vehicles could cooperate to ensure enhanced safety. The majority of traffic accidents occur due to the misinterpretation of others' intentions. With direct connectivity, vehicles could share their driving intentions to each other so to plan accordingly. Under many scenarios where the traffic accident rate is high, such as intersections or lane merging areas, the connected vehicles could actively coordinate actions with each other to avoid collisions. When there are other road participants with limited connectivity and/or intelligence in the scene, the intelligent vehicles can also cooperate to analyze their intentions, conduct joint risk assessment, and develop collaborative driving strategies for enhanced safety. Via their cooperation, the overall efficiency of the transportation resources can also be improved. It should be noticed that the cooperation discussed here is local in the sense that it only involves vehicles that are physically near each and share interests in the same area. The cooperation is self-organizing in nature and involves negotiation among the intelligent vehicles. The structure of the cooperation is highly dynamic. Vehicles are expected to join and leave the cooperation frequently depending on their varying locations and driving interests. The fully connected intelligent vehicles would be in strong cooperation to develop a beyond-the-vision-range or even global situation awareness, which in

turn would better facilitate such autonomous *ad hoc* cooperation.

2) *Regulated Local Competition (RLC):* While cooperation could be beneficial, different road participants are competitive in nature since the transportation resources are limited and all road participants have their own self-interests. Therefore, local competition always exists among different road participants. In the traditional transportation system, the road participants mainly compete for the priority in road utilization, the occupation of parking facilities, and so on. For intelligent vehicles, in low-risk driving scenarios, instead of closely cooperating with other vehicles and following the consensus established by multivehicle coordination, individual intelligent vehicles can carry out predictions on the maneuvers of other vehicles and develop their own driving strategies by taking into account the behaviors of other vehicles. The beyond-the-vision-range or even global situational awareness can take the competition into another level since vehicles in a broader range could be included during this competitive driving strategy development while previously only a limited number of neighboring vehicles would be considered. In the context of the SI framework for transportation, the competition among vehicles is not limited to transportation resources. New dimensions are now introduced into the competition, including the communication, computation, and sensing resources, and the access rights to the global center. While connectivity would be offered pervasively, the communication resources will always be limited and hence the intelligent vehicles need to compete to send and receive information during their cooperation. Similarly, during the cooperation, the intelligent vehicles need to process various information according to the cooperation demand, which may lead to the competition of the computation resources. Furthermore, while the intelligent vehicles can freely share their sensing information with other intelligent vehicles to facilitate the beyond-the-vision-range situational awareness, they could also put priority to sense the areas that are closely related to their current driving interests. For example, if a vehicle wants to change to the right lane, then it probably would be more interested in the area to the right and behind it. Last but not least, while the intelligent infrastructure could greatly facilitate the driving of intelligent vehicles, the vehicles would have to compete for the access to the infrastructure when the number of users exceeds the service capacity of the infrastructure units. All these competitions also bring in a new horizon to the local cooperation among intelligent vehicles. The local cooperation we discussed before would not be the only interactions among the intelligent vehicles. Local competitions coexist with cooperations. It should be noted that all local competitions are subject to the transportation regulatory rules. It is expected that a balance would be reached among the intelligent vehicles with the RLCs.

3) *Coordinated Global Cooperation (CGC):* Besides local cooperation for their immediate driving tasks, the intelligent vehicles could also cooperate with the transportation management center. On the one hand, while nowadays an increasing number of intelligent infrastructures, such as RSU with various sensors, has been installed in the transportation system to facilitate improved transportation, the intelligent vehicles can serve as additional sensors that are distributed and moving across the entire system. They add diversities in both the spatial and temporal sensing information. On the other hand, the connected vehicles would also serve as actuators or controllers for the system in the sense that the control center could utilize them to make an immediate influence on other unconnected and traditional vehicles and hence proactively guide the operation of the entire transportation system. In summary, though the vision range and influence of individual intelligent vehicles are local in nature, when cooperated with transportation management center, they can actively make contributions to the global reliability and safety of the transportation system, which in turn lead to more friendly roads for themselves. Whenever a road participant contributes directly to the ITS control center, GGC happens.

4) *Mandatory Regulatory Intervention (MRI):* For ITS, besides collecting information and cooperating with the vehicles, the transportation management center can also impose regulatory interventions on the vehicles to guide the traffic pattern and the evolution of the entire transportation system. All road participants are subject to MRI. For example, the control center can actively send direct control signals to vehicles, such as rerouting information or lane assignment requests, usually under emergency, congestion, and construction scenarios. It can also intervene the vehicles in relatively indirect manners, such as dynamically adjusting the tolls on some highway portions and broadcasting the pricing information to reduce or increase traffic. Other regulatory interventions include fuel pricing, especially the charging station pricing. These can also affect the individual vehicle driving strategies. The regulatory intervention has been in existence for a long time. But connectivity and intelligence, together with the coupling with the power network would allow this to expand both in scope and scale.

5) *Negotiated Personalized Intervention (NPI):* In the ITS, besides regulatory intervention, the road participants and the transportation infrastructure can interact in the form of personalized intervention. Whenever the control center, who has the global information finds that a particular road participant could do better with its intervention or could benefit the entire system by taking some actions, an NPI could be initiated. From the system perspective, the information collected from all participants in the system can help the infrastructure to provide better informed intervention for individual participants and

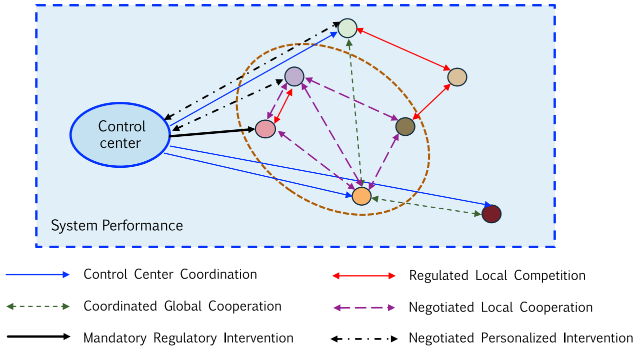

Fig. 4. Illustration of the elements and interactions in a SI system. The background color means that all entities are within the same system and share the same performance provided by the system. Different colors of the entities mean that they have their own self-interests or goals.

personalize the intervention content depending on individual transportation demand and the pertinent current transportation system state. By informing individual participants with global situational awareness, the system-level safety and efficiency can be further enhanced. From the participant perspective, personalized intervention command can be received from the system. It may even be possible for the transportation management center to override local decisions to a certain extent. Note that: 1) the system usually has global situational awareness and hence could more globally address individual participants' transportation need and 2) sometimes the system intervention may at times conflict with the participant's short-term self-interests or personal preferences, but could greatly benefit the evolution of the entire transportation system as well as benefiting the participant itself over the long term. It should be noted that different from the regulatory intervention, the personalized intervention requires the agreement of the participant, possibly via negotiation both offline and real time.

An illustration of the elements and interactions in an SI system is shown in Fig. 4. The various interactions defined in the SI system can facilitate the multiobjective optimization process for a system with many different players, each having its own multiple objectives. The type of interactions can determine the priority order of the objective functions during the optimization process.

B. Features of Societal Intelligence

Compared with existing multientity intelligence frameworks, the main feature of SI is the heterogeneity of the involved interactions. A comparison among the collective intelligence, collaboration intelligence, and our proposed intelligence is given in Fig. 5. Such heterogeneity in the interactions could be further categorized from the following aspects.

1) *Cooperation and Competition:* For the existing multientity intelligence framework, only cooperations among individuals are involved. There is no competition since in both the collective and collaborative intelligence frameworks, individual intelligent entities do not have their self-interests and they share a common goal to accomplish the global system task.
2) *Local and Global:* In the existing collective and collaborative intelligence frameworks, the system can always be treated as one object and only the global interest is allowed. Under the proposed SI framework, entities have their own self-interests and local cooperations and competitions are both involved to serve the local interests.
3) *General and Personalized:* In existing frameworks, the incentive for the actions of all elements is general, in the sense that they all try their best to contribute to the overall system goal and collaborate with each other without any reservation. In our proposed SI framework, in contrast, all cooperations, competitions, and interventions are personalized to the participants involved. The main incentive for the actions of the elements is to serve their own needs and in some sense, the incentive for them to serve the entire system is also to better serve their own needs.
4) *Voluntary and Mandatory:* In existing frameworks, the interactions between the control center and the individual intelligent elements are mandatory. The elements have to exactly follow the commands sent by the control center. However, in our proposed SI framework, most actions of the participants are voluntary except for the regulated interventions provided by the control center.
5) *Individual and System-Wise:* In existing frameworks, the tasks and objectives are all system-wise, while in our proposed SI framework, the individual ones are primary and the system-wise ones are secondary. In the meantime, the secondary ones are meant to enhance the primary ones and can only be achieved at the system level, and individual participants rely on the support and operation of the entire system.

V. THE SI-BASED TRANSPORTATION FRAMEWORK

On the system side, the transportation system is a highly complex system with fast dynamics involving the operations of diverse elements. On the individual side, driving is also a complicated process involving many different tasks. To guide the implementation of the SI application and implementation in ITS, we first divide the driving process into four-layered modules, each with distinct functionalities according to the goals to accomplish the driving tasks and information processed and produced.

1) *Layer 1—Scene Construction:* This layer concerns about the static information about the driving environment. For intelligent vehicles, it involves object detection and identification, road detection, mapping of surrounding areas, and so on; for the ITS center, it takes care of the construction and maintenance of high-definition (HD) maps of the entire transportation system. The HD map would be relatively static and the main task for the infrastructure is to maintain the map and distribute the related map information to various connected vehicles when requested. In summary, this functional module

	Collective Intelligence	**Collaborative Intelligence**	**Societal Intelligence**
Entity to Entity	Designated Cooperation	Coordinated Cooperation	Negotiated Cooperation
			Regulated Competition
Center to Entity	Pre-defined Coordination	Dynamic Coordination	Dynamic Coordination
			General Regulation
			Personalized Intervention
Entity to Center	Homogeneous Contribution	Heterogenous Contribution	Personalized Contribution
			Personalized Request
			Personalized Negotiation

Fig. 5. Interactions involved in ITS in different multientity intelligence frameworks.

provides static *descriptive information* for driving and transportation system management.

2) *Layer 2—Situational Interpretation:* After the construction of the static scene, intelligent vehicles need to further interpret the environment to obtain a dynamic situational awareness. Specifically, an intelligent vehicle needs a good understanding about both the vehicle itself and its surrounding environment. In other words, it needs to understand how they themselves and some surrounding transportation participants evolve over time. The major tasks at this layer would be the mobility tracking of itself and the surrounding objects, the trajectory/maneuver prediction of other participants, etc. At this layer, the ITS center needs to monitor the dynamics at a much larger scale and a coarser resolution. The center needs to track the traffic flows on all roads in the transportation system and predict the evolution of the traffic pattern at the system level. In addition, the center would be interested in identifying and monitoring potential dangerous participants in the system, such as drunken drivers, fatigue drivers, etc. In summary, this functional module provides dynamic *predictive information* for driving and transportation system management.
3) *Layer 3—Scheduling and Planning:* After the situational interpretation of the surrounding environment, an intelligent vehicle needs to conduct scheduling and planning to accomplish its driving tasks. This process could be carried out in a hierarchical manner. First, the vehicle needs to select an overall route to reach its destination. This is typically based upon a preinstalled map and some relatively low-resolution information, such as traffic flow, construction information, and so on provided by the control center. Then, the planned route could be divided into segments. The vehicle could utilize the higher resolution information about its surrounding environment to make a more detailed short-term scheduling and planning on how to reach the segment destination, such as what lanes to take, when to change lanes, how to drive to the next exit/entrance to the highway, what is the action to take at the next traffic light, and so on. Based upon the traffic flow information, the ITS center may send information to the transportation participants to guide the traffic, such as suggested rerouting, expected time to complete a particular segment or reach a destination, and so on. In summary, this functional module provides informative *prescriptive information* for driving and transportation system management.
4) *Layer 4—Online Operation and Control:* Though during scheduling and planning the dynamics of the entire system are well considered, the predicted dynamics are inaccurate and different from the actual ones and adjustments based upon the feedbacks of the environment would be necessary. Vehicles first take actions based on their short-term scheduling and planning strategies. Then, they observe the reactions of the surrounding objects and adjust accordingly. During this process, with a more global picture of the transportation system status, connected vehicles can proactively guide the surrounding unconnected objects that only have a very local understanding of the system. When needed, the ITS center would also send control commands to the transportation system participants to guide the traffic evolution. In this manner, the intelligent capabilities of various vehicles and the ITS center can be fully exploited to improve the overall system efficiency and safety. In summary, this functional module provides online *operational information* for driving and transportation system management.

A more detailed illustration of these functional modules is presented in Fig. 6, where the information exchanged among different vehicles, the vehicles and the ITS center and different layers are shown. It should be noted that the four layers discussed above correspond to the four modules for artificial intelligence realization [42]: "scene construction" corresponds to "perception," "situational interpretation" corresponds to "reasoning and knowledge representation," "scheduling and planning" corresponds to "planning," and "online operation and control" corresponds to "interaction and learning." For the application of the proposed SI framework to ITS, the intelligent vehicles with connectivity and the ITS center would be the main players since they would be able to negotiate

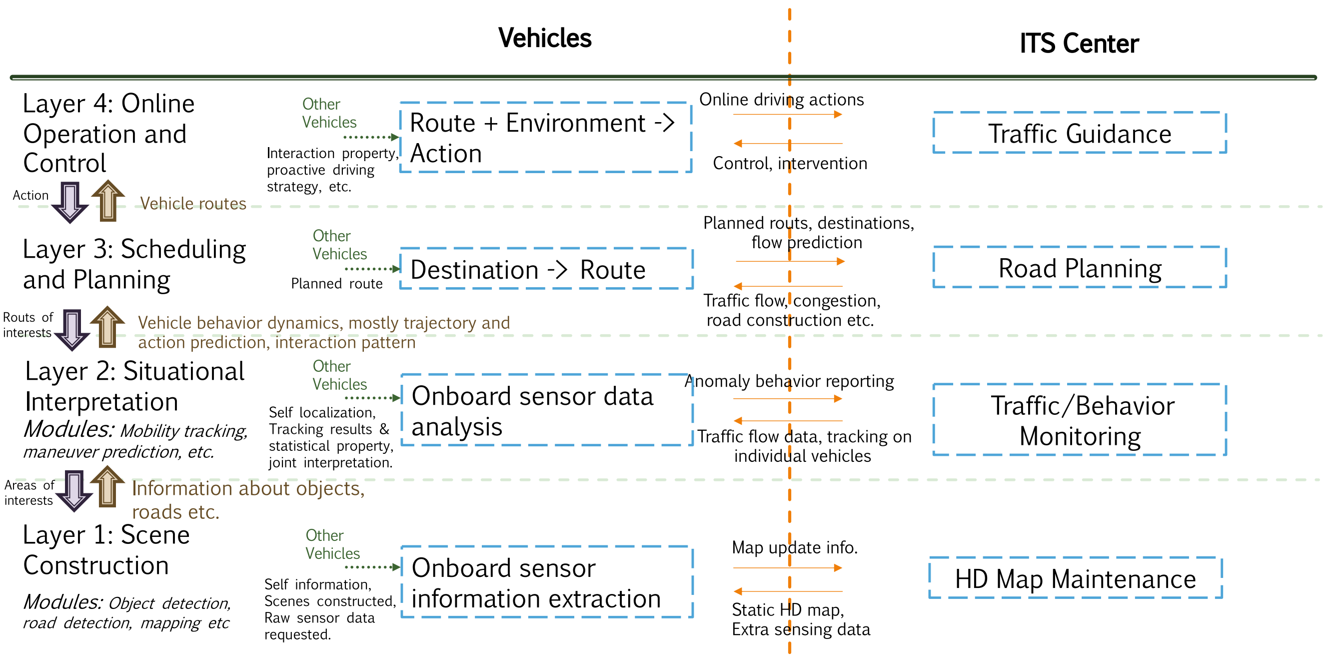

Fig. 6. Hierarchical functional modules for autonomous vehicles and ITS.

with each other and initiate the various interactions within the SI framework. Traditional vehicles and other intelligent vehicles without communication capability would participate in the proposed SI framework indirectly as the passive players in the entire system that respond to the actions taken by the active players in the SI framework.

The multientity SI could be implemented at each layer by introducing the various interactions in Section IV-A among vehicles as well as between vehicles and the ITS center.

1) *Layer 1—Scene Construction:* For the scene construction, autonomous vehicles are usually equipped with plenty of sensors covering the perception of the environment in different directions and areas and with different property. However, due to the cost considerations and the physical limitation of the autonomous vehicles, the range and the accuracy of the single-vehicle sensing can be quite limited. There would be blind spots for the scene constructed by the sensors from a single vehicle and it cannot go beyond the vision range. Within the SI framework, multiple vehicles could negotiate and share sensor data with each other via local cooperation and request necessary data from the ITS center via global cooperation for higher accuracy and beyond-the-vision-range scene construction. The key during this process is that the sensor data across different vehicles are highly heterogenous and with multiple view perspectives, resulting in *multiview multimodal* sensor data fusion (see [43]–[46]). Different from traditional cooperative sensing, under the SI framework, each individual has its specific sensing goals and incentives. Therefore, besides the sensing fusion algorithms, the scheduling of sensing data to satisfy each individual's sensing request under the limited sensing, computation, and communications resources would be subject to local competitions. In addition, the ITS center can harvest information from individual vehicles distributed across the entire system so that the HD map can be constructed and maintained. Meanwhile, it could provide the HD map data to individual vehicles according to their interests. In addition, extra incentives could be provided to some vehicles in some particular areas to provide additional sensing data if the system infrastructure is in lack of sensors or desires a higher resolution in that area. This falls under the NPI from the ITS center to individual vehicles in our SI framework.

2) *Layer 2—Situational Interpretation:* For this layer, autonomous vehicles need to conduct reasoning and extract knowledge about the dynamic evolution of the surrounding objects and the driving environment based upon their raw sensing data, their understanding about objects' physical movements and their reactions to the environment. While a single autonomous vehicle with full intelligence would be able to accomplish this task on its own. The neighboring vehicles could actively and directly send their information to the vehicle, such as their driving intent, their planned actions, and so on. In this way, some of the situational knowledge will be obtained directly rather than being inferred, which greatly increases the accuracy. In addition, when multiple vehicles cooperatively reason over the dynamics, the situational interpretation could be conducted in a more comprehensive manner. The situation over a wider range and with more extensive interaction behaviors could be obtained. While vehicles could cooperatively conduct tracking and behavior analyses on the neighboring vehicles, it should be noted that different vehicles do have interests on different objects due to their own driving tasks. This leads to the local

	Among Vehicles		**Between Vehicles and ITS Center**		
	NLC	**RLC**	**CGC**	**MRI**	**NPI**
Scene Construction	Sensing information for local environment	For comm & comp resources	Sensing information from/to HD map	X	Extra sensing support on demand
Situational Interpretation	Cooperative tracking and behavior analysis	Different priorities in interests	Traffic flow state estimation	Reports on abnormal behavior report	X
Scheduling and Planning	Joint route planning and conflict avoidance	For general transportation resources	General routing guidance	Commands due to construction/emergency responses etc.	Personalized rerouting suggestions for system-wide benefits
Online Operation and Control	General cooperative proactive driving	For general transportation resources	Center-aided cooperative driving	Commands to ensure safety	Personalized driving instructions for system-wide benefits

Fig. 7. Interactions in the SI for ITS in different functional modules.

competition among the vehicles during this cooperative process. The ITS center is more interested in the traffic flow state estimation of the overall transportation system. Traditionally, it relies on the sensors installed on the infrastructure to accomplish this. Now, the local vehicle tracking results could greatly improve the accuracy and resolution of the traffic flow state estimate (see [47]–[49]). Furthermore, the ITS center would be highly interested in some abnormal drivers that can be dangerous to the entire system and hence the local vehicles should report to the center immediately if they detect any abnormal activities in a regulated manner.

3) *Layer 3—Scheduling and Planning:* The scheduling and planning is essentially an optimization process. However, it should be noted that the scheduling and planning for autonomous vehicles is conducted in the context of the evolution of the entire transportation system and hence the optimization should be carried out in the context of a dynamic system over a horizon rather than for a static system at a single snapshot. This makes model predictive control (MPC) (see [50], [51]) a perfect tool to implement this module. While MPC is an extensively studied subject and there are works on distributed and/or cooperative MPC (see [52], [53]), our SI imposes new challenges and creates new opportunities for the MPC: the control/optimization process is no longer for a single-objective function. Instead, each individual adopts its own optimization strategy to optimize its performance. Meanwhile, individual actions will affect the performance of others. In other words, this makes it a *coupled multiuser multiobjective* MPC problem rather than a simple cooperative distributed MPC. Furthermore, the interactions among vehicles at this layer are characterized by both local cooperations and competitions with more tension brought by the competitions among individual vehicles for the transportation resources. How to address the competitions among vehicles at this functional layer in an efficient manner is an important issue for safer and smarter transportation. During this process, the ITS center could provide general route planning guidance since it has a more global view of the entire transportation system. Also, under some special situations, such as road constructions and emergency responses, the ITS center can actively send regulatory commands to vehicles, such as rerouting, lower speed limit, etc. Furthermore, even under normal system operations, for the overall system benefits, e.g., traffic congestion alleviation, the ITS center could also negotiate with certain vehicles to opt for alternative routes by giving them extra incentives.

4) *Layer 4—Online Operation and Control:* For the online operation and control in our proposed societal framework, it is more an interactive negotiation process rather than a cooperative process among the autonomous vehicles. Game theory has recently been plausibly introduced to model such negotiative nature of the interactions among vehicles in transportation systems (see [54]–[56]). However, with our proposed SI framework, there are two main issues to be considered and addressed when applying game theory to model the online operation and control. First, it should be noted that the autonomous vehicles participating in the game also have learning capabilities and could adjust to the environment, while in traditional game theory, the individuals are assumed to be reasonable but always maintains consistent behavior with few variations. Hence, in our proposed SI framework, the entities for the game would be equipped with *reinforcement learning* capabilities and should be modeled accordingly. Second, traditionally, the game would be classified as either cooperative or noncooperative game. However, the interactions within our SI framework have both cooperative and noncooperative nature: on the one hand, each individual works competitively toward its own interests; on the other hand, they would be willing to cooperate to contribute to the benefits of the entire system when these are aligned with its own interests (and fortunately, for transportation systems, this would usually be the case). In other words, within the SI framework, the participants attempt to establish a win–win situation. Third, it should be noted that the players for the transportation system are quite heterogenous. Besides the intelligent vehicles, there are more traditional transportation participants. While these participants would only selfishly act to their

own interests, their actions could be influenced by the intelligent and connected vehicles. With our SI framework, the intelligent vehicles could cooperatively design strategies to proactively guide these participants' behavior so that the overall transportation system would evolve in a healthy manner. This is quite different from the traditional single-vehicle operation and control where the intelligent vehicle passively reacts to the environment. With such a passive mindset, intelligent vehicles only attempt to maintain safety; while with the proactive mindset, intelligent vehicles take full advantage of their intelligence to benefit the entire transportation system. During this process, the local cooperation and competition co-exist among the individual vehicles. Meanwhile, the ITS center could assist the entire driving process by providing more global information on the transportation system. In addition, when necessary, the center can actively intervene selected vehicles with commands if the safety of some individuals is threatened. Furthermore, it should be noted that during the proactive driving process, though the intelligent and connected vehicles could actively affect other vehicles, they are doing so to maximize their own benefits rather than the entire transportation system. If needed, the ITS center could also utilize the connected vehicles to influence others via negotiation. Even though this might sacrifice the vehicles' self-interests, some rewards could be provided to them so that they would be willing to participate.

In summary, for the vehicular participants in ITS, we have identified four hierarchical function modules corresponding to the four components of intelligence and each function module can be enhanced with our proposed intelligence framework as shown in Fig. 7. The vehicles working under our proposed intelligence framework are expected to establish a win–win situation among themselves and the entire transportation system via their local cooperations, regulated interventions, and personalized interventions to address the tension of local competitions.

VI. CONCLUSION

In this article, for vehicular participants in ITS with mixed intelligence and connectivity, we have proposed a new multientity intelligence framework termed as the SI. The features of the SI and the unique interactions among entities within the SI framework have been discussed in detail. Its application to ITS in terms of the four distinct functional modules of deriving has been provided, together with the unique challenges and opportunities therein. The proposed SI framework can also be applied to similar systems involving heterogeneous entities with both local and global interests. For example, the interactions among different players in power systems can also be characterized by the proposed SI framework, where different players share the same grid infrastructure but are taking actions based upon their own incentives.

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