Distributed Control in Multi-vehicle Systems

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ABSTRACT

The Southwest Research Institute (SwRI) Mobile Autonomous Robotics Technology Initiative (MARTI) program has enabled the development of fully-autonomous passenger-sized commercial vehicles and military tactical vehicles, as well as the development of cooperative vehicle behaviors, such as cooperative sensor sharing and cooperative convoy operations. The program has also developed behaviors to interface intelligent vehicles with intelligent road-side devices. The development of intelligent vehicle behaviors cannot be approached as stand-alone phenomena; rather, they must be understood within a context of the broader traffic system dynamics. The study of other complex systems has shown that system-level behaviors emerge as a result of the spatio-temporal dynamics within a system's constituent parts. The design of such systems must therefore account for both the system-level emergent behavior, as well as behaviors of individuals within the system. It has also become clear over the past several years, for both of these domains, that human trust in the behavior of individual vehicles is paramount to broader technology adoption. This paper examines the interplay between individual vehicle capabilities, vehicle connectivity, and emergent system behaviors, and presents some considerations for a distributed control paradigm in a multi-vehicle system.

Key Words: Cooperative Vehicle Systems, Cooperative System Dynamics, Intelligent Vehicles

1. INTRODUCTION

Vehicles are becoming more intelligent with the proliferation of in-vehicle technologies and advancements in perception, reasoning, and actuation technologies. The "Intelligent Vehicle" domain is being driven by a number of factors, not the least of which is consumer demand for more driver-assist and active-safety capabilities in their vehicles. Vehicles are also becoming more connected through communication technologies sponsored by the USDOT and the Connected Vehicle program, which seeks to develop standards and technology for in-vehicle, and roadside, radio devices. These devices allow vehicles to communicate with each other (V2V), and roadside devices (V2I) in a variety of ways, for a variety of purposes. The convergence of these two domains however is creating a third type of application domain, the cooperative vehicle system (CVS). A CVS is altogether a different technology than either the Intelligent or Connected vehicle, and yet even as these two constituent technologies race ahead, little work is being done to understand the broader system effects that will emerge when these technologies reach a critical mass, or a tipping point in the jargon of complex systems.

SwRI is an applied research and development non-profit organization, and the Intelligent Systems Department at SwRI has been conducting internally- and client-funded R&D in the areas of "intelligent vehicles", "connected vehicles", and "cooperative vehicle systems", for a number of years. This paper will discuss SwRI's research in these areas, and will focus on the design considerations for cooperative vehicle systems with respect to the broader system dynamics that can emerge. As the constituent technologies are more broadly adopted, the interaction between devices will have an increasing effect on system-wide behaviors, which will then have a feedback effect on the behaviors of individual devices.

The SAE Dedicated Short Range Communications (DSRC) Traffic Information Group Sub-Committee is developing standards for traveler information and vehicle teaming. Efforts are underway to standardize transportation-related information messages displayed for the driver, and SwRI actively participates in these efforts. Research conducted at SwRI has implemented the emerging SAE message set on a three-vehicle platoon, one of which was the MARTI-1 autonomous commercial vehicle (the MARTI software has recently been ported to a military HMMWV). Simulations of larger platoons have also been created, and have provided valuable insight into the effect of vehicle-to-vehicle communication on overall system stability.

Traffic system dynamics have been thoroughly examined in the literature for decades [1] - [4], through both empirical and formal methods. As vehicle population and density increases, and our urban centers become choked, economic and environmental factors become critical for decisions related to urban planning and infrastructure; however, so long as the individual vehicles are controlled by individual drivers, the overall efficiency of dense traffic systems will remain low. This is a property of the system that emerges as a result of interactions between vehicles within their environment. Emerging intelligent vehicle technology, from active safety systems, to inter-vehicle communication, to autonomous capabilities, is enabling a higher degree of connectedness and cooperation among vehicles, which will affect the system-level behavior and performance. However, if a systems approach is not taken in the design of these systems, particularly as they relate to their interaction with other vehicles or roadside devices, undesired system-level effects may emerge.

2. Intelligent Vehicles

The concept of intelligent vehicles encompasses a wide variety of paradigms and technologies, but simply stated are vehicles that possess hardware and software, which enable them to in some way sense their environment, reason on that information, and provide some feedback to the environment, which a typical observer would deem "appropriate" [9]. Thus intelligent vehicles encompass not only the enabling hardware and software, but a design philosophy that this machine will perform an action in a human-relevant

however, stand-alone intelligent vehicle technologies have been driven primarily by automobile manufacturers (OEMs), and sluggish consumer demand. So long as the human still has control of the vehicle's functions, there hasn't been a large demand for the vehicle to take over these functions. Cruise control is a nice feature, which is an intelligent vehicle technology that has been around for a while, but adaptive cruise control, where the vehicle will also maintain a safe following distance from vehicles in front of you, has just recently been introduced, and is not yet widespread [5]. Parallel parking assist is another good example of an intelligent vehicle technology building block. This system uses cameras and software to interface with drive-by-wire capabilities within the vehicle, to self-park. Although useful, a self-parking car by itself is still relatively isolated in its impact the intelligent vehicle domain. Automatic braking systems and traction control are other examples where humans have relinquished control of vehicle functions to hardware/software systems, and the vehicles make decisions within tens or hundreds of milliseconds, and then take "appropriate" action.

These technologies are often developed for safety, comfort, or both. But their development is leading towards a vehicle that is very "aware" of its internal state and surroundings, and with the right software, is able to make decisions quickly, and make physical adjustments to the vehicle's speed and trajectory. The natural progression of this technology is towards fully autonomous vehicles. The challenge in this progression, however, manifests as more human control is relinquished. More trust has to be given over to the system that it will sense the correct parameters in the environment, processes that data appropriately, asses potentially complicated situations, and then make the "right" decision. However, as researchers in this technology, it's easy to see why there is hesitation to relinquish this trust. Human drivers do not always make the "right" decision, and yet we will hold our technology to a much higher standard. And one of our most significant challenges currently is defining the bounds with which our technology will operate to a sufficiently high degree of certainty to pass the "trust test".

3. Connected Vehicles

The concept of connected vehicles is similarly fairly simple, with a more complex application. According to the Research and Innovative Technology Administration (RITA), connected vehicles are vehicles that are equipped with communications technology, which enable the communication between other vehicles (V2V) and with properly equipped roadside devices (V2I). The communication technology in the United States is called Dedicated Short Range Communications (DSRC), and is based on the 5.9Ghz frequency. However, simply allowing vehicles to communicate with each other or roadside devices, does not necessarily make them "connected". The connection comes when a message is successfully passed between two devices. And even then, there may be no further relevance if, for example, the message is invalid. When researchers talk about connected vehicles, again they are not only referring to the hardware and software enabling technology, but to a design philosophy. A connected vehicle is a vehicle with access to information that has been gathered and processed by a completely separate entity. This means the information has the potential to expand the vehicle's awareness of its surroundings in a way on-board sensors could never do. Connected vehicles have the ability to share information about other vehicles, or about their local, or non-local environments. The applications for this are quite environment, usually for the benefit of the human occupants. The means with which this is accomplished is varied; expansive, and are the basis for the USDOT Connected Vehicle program.

SwRI has been conducting R&D in connected vehicles for a number of states DOT, as well as commercial vehicle OEMs. Some of the applications are safety-related, such as merge assist, where vehicles communicate to avoid a collision at a highway on-ramp, or in signal phase and timing (SPAT) applications, where vehicles and roadway devices can warn of an impending red-light violator. Other applications are for efficient operations, such as in fleet management, where roadside and vehicle data can be used to assist in re-routing a commercial vehicle to avoid a long and costly delay. Still other applications are targeted for traffic management systems operators, where semi-real-time aggregate data from vehicles can calculate travel times, help uncover developing congestion, or pinpoint the location of an accident. In this case, the previous example is relevant, and other vehicles could be warned and re-routed to avoid the affected route.

One aspect of connected vehicles that begins to hint at the potential of cooperative vehicle behaviors is that of "vehicle teaming". The SAE DSRC Traffic Information Group Sub-Committee is developing standards for traveler information and vehicle teaming. Efforts are underway to standardize transportation-related information messages displayed for the driver, and SwRI actively participates in these efforts. Research conducted at SwRI has implemented the emerging SAE message set on a three-vehicle team, one of which was the autonomous MARTI vehicle. Simulations of larger vehicle team have also been created, and have provided valuable insight into the effect of vehicle-to-vehicle communication on the overall team's string stability, which can also lead to effects of greater fuel efficiency and reduced carbon emission for gas-powered vehicles [4],[6],[7].

4. Cooperative Vehicle Systems

Cooperative vehicle systems are an even more abstract concept than intelligent or connected vehicles. CVS are comprised of individual devices, such as the vehicles and road-side devices we've been discussing, which function together as a cohesive system using their own independent control systems and sets of objectives toward one or more collective goals. Often-times the behavior of a cooperative system, whether it's a vehicle system or not, can seem non-intuitive, and can relatively quickly change from one point of apparent equilibrium to another. These rapid transitions have been studied extensively in the literature for a wide variety of complex, interconnected systems, and are prevalent in dynamic systems where a forcing function is present. Traffic systems in general are good examples of complex systems, which form self-organizing patterns, and can rapidly change states based on a minor perturbation.

Cooperative vehicle systems can thus be approached from different scales. A single team of vehicles moving down the roadway may be considered a CVS depending on how they are teaming. An entire urban network of traffic could also be a CVS. SwRI has developed several example technologies that can be used to one extent or another as part of a CVS. These technologies build on both the intelligent and connected vehicle technologies, but take the next step of enabling vehicles to seamlessly integrate information obtained from other sources into their own world model. Specifically, SwRI has developed several systems for demonstrating the benefit of CVS.

One system enables vehicles to cooperatively share sensor data concerning objects of interest in their environment with other vehicles that are nearby. The use-case SwRI highlighted was pedestrian collisions on roadways due to pedestrians crossing a road illegally. This was demonstrated using small research vehicles with our partners in France, and on the full-size MARTI vehicle in New York City at the ITS World Congress in 2008. A second system we developed is the cooperative convoy system (CCS). This system has a passive and an active component. The passive component is an algorithm that keeps track of which vehicles are in the team and which physical position they occupy, and can provide this data to a user interface for driver information. This passive system was demonstrated at the ITSA Annual Meeting in Washington, DC in 2009. The active component is geared towards vehicles with greater autonomy, and enables autonomous vehicles to send commands to other vehicles in the team to, for example, rearrange the team order. This was demonstrated at the Robotics Rodeo at Ft. Hood in 2009 and at Ft. Benning in 2010, where the MARTI vehicle and two other vehicles were shown to maintain a convoy, and the vehicles could rearrange, or even leave and rejoin the convoy based on the required mission. SwRI is currently working to expand the capabilities of these systems based on commercial and military requirements.

SwRI has also conducted research into the dynamics of large-scale urban traffic systems, and how the technologies of intelligent and connected vehicles might affect these dynamics [8]. Using an agent-based modeling approach, SwRI investigated the effect of increasing the vehicle population that is enabled with connected vehicle technology. The percentage of vehicles equipped with the technology was varied from 0% to 100%, and the model enabled the collection of numerous system-level parameters, such as congestion. In May of 2006, the U.S. Department of Transportation (USDOT) outlined a multi-tiered effort known as the "National Strategy to Reduce Congestion on America's Transportation Network" [23]. This is commonly known as the "Congestion Initiative." The first phase is focused on relieving urban congestion. In conjunction with this effort, RITA is continuing its initiative to improve safety and mobility on the nation's roadways by supporting efforts to integrate standardized traffic management communication infrastructure with vehicle systems. The efforts by RITA and others, including work done by SwRI, to develop infrastructure and vehicle-to-vehicle (V2V) technologies is critical to advancing the intelligent traffic system model. SwRI's research using the agent-based model approach was targeted at answering some of the non-intuitive questions that arise with large-scale traffic systems. One such question is what level of deployment, or market penetration, is required before system-level benefits can be observed. Many other complex systems exhibit the ability to change phases, shift from one state of equilibrium to another, when between 5% and 10% of the constituent parts are affected [13],[14].

If traffic systems are similar, this would bode well for both the commercial OEM interests and the Government agencies looking to deploy technology, because the current thinking in some circles is that 100% deployment is necessary. SwRI's model found that congestion was positively affected when at least 10% of the vehicles were able to communicate with other devices, and that a level of 25% created even lower congestion. The model's limitations however, such as restricted route choices for congested vehicles, created an effect of increasing congestion when 50% to 100% of the vehicles were equipped. This was due to the vehicles having limited routes to choose from, and ultimately selecting the same routes as many other vehicles. SwRI is working to expand the capabilities of this model to include more realistic route choices on the scale of a large urban traffic network, but we feel confident in the vehicle agent behavior model, and that it will scale well. Some of the perception and intelligence algorithms used on the MARTI autonomous vehicle were modified and included as part of the vehicle agents' algorithms. Each agent was also created with slightly different characteristics, for example, individual propensities to travel slightly faster or slower than the posted speed limit. Small random fluctuations in some vehicle parameters were also included to introduce stochastic noise into the vehicle's behavior.

This model was also used to show how teams of vehicles could travel together using V2V communications with the result of increased string stability. This has a significant impact on fuel economy and carbon emissions since vehicles moving at more constant speeds, rather than the oscillating speeds found in unstable vehicle strings, are more efficient. Again, the ABM and simulation allows us to collect data such as fuel usage and carbon emission from individual vehicle agents, which can then be aggregated to the larger traffic system.

In contrast to centrally planned traffic management systems, none of the individual devices in a CVS need contain an understanding of global events or objectives, and emergent behavior plays a bigger role in the overall system's dynamics. Development of cooperative vehicle systems requires an understanding of how the behaviors at the device, or vehicle, level will affect the overall system behavior, and conversely, how that will then feedback to the device level.

5. Distributed Control

The ability to share information among devices plays a critical role in the emergent behavior of decentralized cooperative systems [8],[10], and subtleties such as communications latency, message content, and density of devices will significantly affect the overall performance of the system. All of these are critical components to consider in the development of a CVS. However, those components provide the structure of the system, but the behavior of the system will emerge as a result of how that structure is used. In other words, the behavior of the devices, in this case the vehicles, within the context of this information-rich environment, and within the confines of the physical traffic infrastructure will determine the emergent system properties. Control of such a system cannot be managed as a centralized system with master and slave devices. The "intelligence" in the system cannot be maintained at a central server and then dispatched to devices for them to mindlessly carry out the new instruction. This control paradigm will fail, and has been shown to fail in other domains [11],[12],[19]. One of the greatest weaknesses, for example, in the US power grid is its centralized command and control nature, and is why the "SmartGrid", and other decentralization efforts have been underway for a number of years [20],[21][22]. Similarly, a complex, interconnected traffic system will be robust and fault-tolerant if it is under decentralized control.

The SwRI cooperative convoy system was developed with this paradigm. In the SwRI CCS, the same set of algorithms run on every vehicle in the team. There is no "leader" vehicle, which determines and keeps track of the make-up of the team, which is then "pushed out" to the team members. The CCS developed and demonstrated by SwRI uses a distributed control architecture that is robust and fault-tolerant. Every vehicle in the team runs the same CCS software, which at a rate of about 20hz determines the position, speed, heading, and team position of every vehicle in the team, including the self-vehicle. The algorithm uses nothing other than the vehicle heartbeat message from other vehicles, which contains various parameters including the GPS position and speed of the vehicle. This message is based on the SAE J2735 standard for Dedicated Short Range Communications (DSRC) Message Set Dictionary, and a simple calculation allows the vehicles to properly sort the vehicles in the team. This is important because the CCS was developed such that active vehicle sensors are not necessary, such as LIDAR or cameras. With this calculation, a vehicle can determine which vehicle it is directly following, and can adjust its speed accordingly to maintain a desired following distance. The team ordering also allows vehicles to “sense” speed changes of any vehicle in the team, as soon as they are reported by that vehicle as part of its heartbeat message. With this type of information, vehicles can react to speed changes in vehicles that are not directly in front of them, which means, the entire team can now react as a single cohesive unit if, for example, the front vehicle slows suddenly.

Human drivers can be slow to react, or may overreact to a vehicle slowing in front of them, and this reaction continues for each new vehicle entering the situation. This is how a small perturbation in dense traffic can be amplified into major, long-lasting traffic jams. Vehicle teams that are communicating position and speed changes numerous times a second can be less susceptible to this effect through a more parallel vehicle reaction, rather than each vehicle reacting in series. Since each vehicle in the team maintains its own accounting of the team structure, the loss of a vehicle from the team is not catastrophic. Autonomous convoy scenarios usually involve the concept of a “leader vehicle”, which the others follow, which inevitably leads to questions about what happens to the follower vehicles if the leader vehicle is “taken out”. In a military sense, this could occur due to hostile action or equipment failure. In a commercial sense the convoy fails if the leader vehicle leaves the convoy for some reason.

The CCS software was developed for both commercial and military scenarios. The military convoy scenario contains a second message set that is sent only when triggered, and contains a command structure, which is a new instruction and is targeted at a specific vehicle. This command may be for a specific vehicle to increase or decrease its following distance, to follow at a lateral offset, or even to change its position within the team structure. There is still no “leader” vehicle in this scenario; however, a single vehicle is given command authority to issue this command message.

Information is a crucial aspect in the behavior of a cooperative system. Depending on the communication structure of a cooperative system, individuals may use direct and/or indirect (stigmergic) forms of communication. Typically, stigmergic communication takes the form of one individual modifying the environment, and another individual sensing that change and reacting to it. In a cooperative vehicle system, this may take many different forms. But one form in particular is relevant to the connected vehicle technology we’ve been discussing, and that is communication via an infrastructure-based devices, or Roadside Equipment (RSE), which is essentially a DSRC radio. The function of this type of device is to provide a communication bridge between nearby DSRC-equipped vehicles and other vehicles, which are too far away to be communicated with directly. Information collected by an RSE is usually sent to a central traffic management system, which can then distribute the information to other RSE devices. The net effect of this communication structure is that vehicles have access to information that is difficult or impossible to collect themselves, but persists within the CVS environment due to the storage and broadcast capabilities of the RSE devices.

Indirect communication introduces large latencies of course, but the information transmitted in this way is not meant for real-time use, but is used for more deliberative planning. For example, a vehicle may directly sense heavy congestion, which can be relayed to all other DSRC devices within the limitations of the DSRC equipment. This may include other vehicles and RSE devices, but eventually the information that a specific segment of road is experiencing significant congestion makes its way into the larger system repository of information. Further upstream of the congestion, a separate RSE device receives the information and begins locally broadcasting it, where nearby vehicles can receive it, and then use it for route planning purposes. In an effort to better understand the issue of communications latency, and the resultant emergent behavior on CVS, SwRI has developed and demonstrated a number of connected vehicle scenarios, most recently at the ITS World Congress in Orlando, FL.

SwRI is currently conducting research into cooperative vehicle behaviors for autonomous vehicles within military-relevant scenarios using the two MARTI vehicles, one commercial and one military, as well as other vehicles in SwRI’s fleet that are equipped with the connected vehicle device technology. Again, the approach with these scenarios is to enable the intelligence to reside at the vehicle level, but to approach the design of the vehicle interaction such that the collection of vehicles accomplishes the mission. A mission of perimeter patrol for example might have several vehicles, with different perception and locomotion capabilities. If the goal of the system is to patrol a perimeter, and presumably either alert on or pursue a detected anomaly, a centralized control paradigm would require a leader, either a leader vehicle or human operator, to coordinate the activities of all the vehicles, assimilate their data, assess their situations, and then send out new commands. A distributed control paradigm would enable each individual vehicle to sense and react to its own environment, while sharing “relevant” information with the other vehicles. What information is relevant is determined by the developers of the system, as are other parameters such as how much information is shared, and how often.

Developers must also determine what action should be taken. This is the behavioral design aspect of the system, and is not necessarily intuitive. For example, if all of the vehicles have a simple behavior that causes them to navigate to a location when another vehicle detects something, the system can be fooled by a false detection, or by purposely creating a diversion, which attracts all of the perimeter patrol vehicles to one location, leaving the rest of the perimeter unobserved. And depending on how many vehicles there are and how big they are, etc, they may all get stuck trying to get to the location. Alternatively, if the vehicles have a slightly more sophisticated behavior that enables only the closest vehicles to the location to go inspect the report, and then, only to a max number of vehicles, this diversionary, or false-positive, effect can be avoided. In this case, no “leader” vehicle told which vehicle to go where, the vehicles collectively decided who goes and who stays, and the decision is largely based on the circumstances of the event, the environment, and their individual capabilities. This scenario can be enhanced further through a simple feedback mechanism. If the first vehicle on-scene confirms the initial report, the “weight” of the report is increased. The vehicles could have a behavior modifier that causes them to react more quickly and decisively as the “report weight” increases. It’s not likely a false-detection, although it could still be a diversion.

This feedback mechanism is often seen in the response of social insects [14] - [18]. Ant species will use this to find the best food source or nest site, and bees use this mechanism in the defense of their hives. When a bee stings it releases a pheromone, which attracts nearby bees to sting, which continues in a reinforcing feedback loop [15]. The net effect is that the entire hive is quickly engaged after the first sting has occurred, and the threat is quickly overrun with stings. This effect is considered a form of collective intelligence because the collective acted as a cohesive unit to sense and react to something in the environment, which no single individual could have fully sensed or reacted to. When an ant column selects one path to a food source over another, it is using the intelligence of the collective to do so, since no single ant has explored all possible paths, calculated the speed for each, and determined a winner. Rather, faster ants come back quicker, laying chemical signals faster, which are reinforced by other returning ants. The best trails simply get more pheromone, and the ants are predisposed to follow the strongest chemical trail.

One of us (Garcia) has also conducted research in the cooperative control of unmanned aerial systems (UAS) using rotorcraft. A simulation was developed where a manned aircraft was teamed with a small group of smaller, unmanned aircraft (UA). The specific goal was to have the UA dynamically assemble into standard flight formations with the manned aircraft during flight maneuvers [25]. The small group of UA were developed with two main behaviors: Obstacle avoidance and desired position. Obstacle avoidance was triggered when a UA flew to within a minimum radius, and was implemented by calculating non-linear repulsive potential fields for each aircraft, which of course assumes a 360 degree situational awareness for the aircraft. The behavior for maintaining a “desired position” simply attempted to maneuver the vehicle to within a desired offset location of all other vehicles, again using the potential field method.

The desired offset was calculated by summing the repulsive potential fields from the obstacle avoidance behavior with an attractive potential field generated from a goal position, which was implemented as a dynamic variable, dependent on the formation type and local lead position [24]. The unmanned aircraft were specifically restricted to state information about their local lead aircraft, which similarly to the CVS was the vehicle directly in front of the aircraft. These local lead aircraft were dynamically selected by the order in which they joined the formation. Using the formation type, each UA could determine its constant offset from its local lead, and combining this information with the local lead’s state data allowed each UA to determine the current goal position in the absolute coordinate frame [26].

Although this method allowed the group to successfully form correct formations, several severe and sometimes dominant emergent behaviors developed. Specifically, experimentation showed that dynamic motion of one vehicle would cause perturbations within the position of the other aircraft, which due to the control techniques used were not immediately damped. Each aircraft was essentially responding only to the movement of its nearest neighbor, without any understanding of the motion of the group as a whole. This is an identical result as we observed with the string stability of vehicle systems. In the UA system, additional complexity is seen in the formation stability since it can encompass three spatial dimensions, whereas vehicle systems typically only deal with a single dimension, forward, except in the case where a vehicle is following at a lateral offset, or wingman configuration, as SwRI has also demonstrated. The formation of aircraft systems can easily two or three dimensional aspects, and the reaction of a rotor craft to, for example, avoid another aircraft, can certainly take advantage of multiple dimensions.

In an effort to suppress the emergent formation instability, each vehicle also had a third behavior for predicting the intent of other aircraft. Prediction of future motion was based on the orientation of other vehicles, which was possible because the unmanned aircraft were physically identical, and thus would have similar performance characteristics. This orientation cue provided a small decrease in the latency of communicated intent from other aircraft, which allowed the system perturbations to be damped more quickly. Further damping could have been realized by enabling a direct communication link among aircraft, where the intended travel vector could be communicated quickly to the other vehicles in the system, and the system of aircraft could move together as a single cohesive unit.

6. Conclusions

The development and deployment of cooperative vehicle systems provide new challenges for researchers, device manufacturers, and policy makers because the behavior of large-scale cooperative systems emerges as a result of spatio-temporal dynamics within the system’s constituent parts, and is heavily influenced by the environment in which it operates. A systems approach must be taken, and adopted as early in the development process as possible, to ensure the performance of such systems operates within agreed upon constraints. Commercial and military applications alike will require this kind of assurance for broad acceptance to occur. Southwest Research Institute is actively working in the areas of intelligent vehicles, connected vehicles, and cooperative vehicle systems to assist in the transition of these technologies to commercialization and broad acceptance. Central to the successful deployment of these technologies, however, is the broader issue of distributed control in multi-vehicle systems, especially when the system consists of mixed-type vehicles, such as when the vehicles in a system range from fully manned, to semi-autonomous, to fully-autonomous. This control strategy cannot take the form of deterministic heuristics; rather, it must be approached from the standpoint of a decentralized system, where individuals behavior deterministically for a given input, but the system as a whole exhibits emergent behavior.

This paper has discussed some of the research performed by SwRI, and examined the interplay between individual vehicle capabilities, vehicle connectivity, and emergent system behaviors. Considerations for a distributed control paradigm in a multi-vehicle system were also presented within the context of recent and active work being performed at SwRI.

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