Intelligent Vehicle Behavior and Emergent System Stability

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ABSTRACT: The Southwest Research Institute (SwRI) Mobile Autonomous Robotics Technology Initiative (MARTI) program has enabled the development of a fully-autonomous passenger-size vehicle, 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. Development of intelligent vehicle behaviors must be understood within the context of broader traffic system dynamics. This paper examines aspects of behavioral stability for traffic systems that are comprised of intelligent vehicles and other intelligent devices that will enable stability in the emergent system behavior.

Key Words: Safety, Cooperative Vehicle Systems, Cooperative System Dynamics, Intelligent Vehicles [C1]

1. Introduction

Traffic congestion tends to increase proportionally with population and prosperity. In the United States, new highway capacity has not kept pace with population growth. Between 1980 and 1999, total highway miles grew by only 1.5 percent while total vehicle travel mileage increased 76 percent. For many years, the automotive industry and federal and state departments of transportation have been developing systems to tackle safety and mobility problems in their respective domain. Many new automobiles have advanced vehicle safety systems that enhance driver perception and driver response to some degree. In the public sector, meanwhile, complex Intelligent Transportation Systems (ITS), also known as “intelligent highways,” enhance traffic flow. While these systems have each made positive steps toward reducing fatalities and congestion, many within the ITS community believe the greatest benefit could be realized through coordination between vehicles and highway systems and among vehicles themselves. These systems are referred to as “Cooperative Vehicle Systems” (CVS).

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 is the autonomous MARTI vehicle. 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, 2, 3], through both empirical and formal methods [4]. 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 [5]. 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, are 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. Cooperative Vehicle Systems

Cooperative vehicle systems are comprised of individual devices, such as vehicles and road-side devices, which function as a cohesive system using their own independent control systems and sets of objectives toward a single, collective goal. In contrast to centrally planned traffic management systems, none of the
individual devices in a CVS need contain an understanding of global (system-wide) events or objectives; rather, physical and behavioral characteristics at the device level produce emergent behaviors at the system level. Development of cooperative vehicle systems requires an understanding of how behaviors at the device level affect the overall system behavior, and conversely, how the goals and objectives set at the system level will to some extent drive device-level design.

2.1. Traffic Dynamics

Modeling traffic system dynamics can be very complex; considering a number of factors that affect the aggregate flow, such as vehicle density, road width, bend radii, obstructions, detours, etc. Approaching traffic system modeling at a macro level and applying averaging assumptions, the model results will only be valid within the bounds of the averaging assumptions and will not give the modeler flexibility to investigate system-level effects that emerge from the individual vehicle capabilities. To effectively model traffic system behavior as it is related to the capabilities and behaviors of individual vehicles requires an understanding of how internal dynamics of complex systems interact to produce system-level phenomena. Agent-based modeling is one such tool that allows the individual to be characterized and a number of individuals to interact in space and time to produce emergent system behavior. Agent-based modeling (ABM) is a commonly used approach in microscopic modeling to capture traffic interaction behavior. In ABM, a system is modeled as a collection of autonomous decision-making simulation entities called “agents”. Figure 1 shows two simple behavior state charts, which have been developed for vehicle agents as part of a traffic system ABM.

![Figure 1 ABM Vehicle Behavior State Charts](image1)

Each state chart contains behavior states (boxes) and transitions between behaviors (connecting lines). The underlying code is written in Java, and each behavior state and transition contains specific code that is executed when triggered. The vehicles have simple behaviors of traveling along a route, maintaining a following distance if there is a lead vehicle, and changing routes. A road network environment was created to force the classic merging vehicle problem, as well as the effect of periodic slowing vehicles on a single-lane road due to a route change. Figure 2 shows the model during run-time with a vehicle population of 50, with vehicles traveling from left to right. The target speed limit on the roadway network is 40mph, and when vehicles transition from one path to another, they slow to 10mph. The center section where paths intersect is shown at a higher zoom level above the main road network. The color of the vehicles represents their individual velocity condition, where green indicates the vehicle is traveling at its desired speed, yellow indicates the vehicle is traveling between 5mph and 10mph slower than its desired speed, and red indicates the vehicle is traveling slower than 10mph from desired speed. One effect of these simple behaviors within the vehicle population on the overall traffic system efficiency is collected and shown in the

![Figure 2 Traffic System (50 vehicles)](image2)
inset graph, and represents the ratio of velocity to desired velocity averaged over all vehicles. As the system becomes more congested, this value drops. The transition points where paths intersect cause vehicles to slow and even stop depending on the vehicle density. Figure 3 shows the effect of adding just 10 more vehicles to this system. A jam develops extending back beyond the first intersection point, and the average velocity ratio drops significantly. The vehicles in this system also exhibit classic “stop-and-go” traffic behavior during run time, and the “slinky” effect where strings of vehicles compress and elongate as they respond to the vehicle directly in front of them. The slinky effect is more formally known as a phenomenon of the stability of dynamic systems of vehicle strings [4, 6].

This effect has been modeled before [7], although not necessarily from the standpoint of agent-based modeling. Some of the perception and intelligence algorithms used on the MARTI autonomous vehicle have been modified and included as part of the vehicle agents’ algorithms. Each agent is also created with slightly different characteristics, with individual propensities to travel slightly faster or slower than the posted speed limit. A small random fluctuation in the target velocity is also introduced for each agent at each time step to introduce stochastic noise into the vehicle’s behavior.

2.2. Vehicle-to-vehicle (V2V) Communication

The ability to share information among devices plays a critical role in the emergent behavior of decentralized cooperative systems [6], and subtleties such as communications latency, message content, and density of devices will significantly affect the overall performance of the system. The behavior modes can now be affected by information received from external sources, the nature of which must be evaluated for relevance and authenticity, and appropriate action taken. Incoming messages are received and parsed depending on the nature of the message. This may include whether the message is from another vehicle or an infrastructure device, a broadcast or direct message, a request for information, or
The characteristics of DSRC make it an especially effective option for cooperative vehicle systems such as teaming because of the inherent features of DSRC: a dedicated spectrum, channel switching, low latency, fast network acquisition, and secure communications. Direct vehicle-to-vehicle communications using DSRC provides an effective means of event and roadway situational awareness including slow downs, accelerations, or obstructions. Figure 5 shows a simulation of a five-vehicle team of vehicles, which individually are attempting to maintain a following distance to the vehicle in front using data transmitted over DSRC formatted in the SAE cooperative cruise control (CCC) message set. The white circles represent the vehicle’s GPS accuracy, which also varies per vehicle, and affects the vehicle’s ability to maintain an accurate absolute position within the team. This has the effect of increasing the overall error on team length (inset), and could introduce the possibility of non-team vehicles cutting in and disrupting the team formation.

SwRI implemented the teaming algorithms on the MARTI autonomous vehicle, as well as on portable kits that were installed in manned vehicles (Figure 6).

Empirical results showed good correlation to simulation, with decreased vehicle following distance error when the V2V communications were enabled. Figure 7 shows some results from this testing, with a varying lead vehicle speed, and the resulting following distance compared to the target following distance. “D” illustrates points where temporal delays were noted in the response of the portable user interface. These results could be further improved through the implementation of a sliding-mode controller.

The agent-based model discussed above was then run again with a vehicle population of 60, but vehicle-to-vehicle communication was enabled, which in this case simply allowed the vehicles to match the velocity of their individual lead vehicle, rather than modifying velocity based on changes in the following distance. The effect is shown in Figure 4, and shows an increase in the ability of the vehicles as a whole to maintain their target following distance, regardless of speed fluctuations due to turning vehicles. This simplified model represents an ideal case because...
communication delays and vehicle acceleration are not considered. Delays in communication, message processing, and due to vehicle inertia, serve to interject temporal delays in information processing within this kind of coupled decentralized system. However, coupling vehicles together via low-latency communications will have a dramatic effect on the overall traffic system efficiency, which has ramifications throughout society.

3. Future Work
Southwest Research Institute is conducting research into the behaviors of complex traffic systems, and how those behaviors emerge as a result of both the highway infrastructure, and the behavior of individual vehicles. This research will provide insight for organizations that build both highway infrastructure, and intelligent vehicles. Complex decentralized systems will operate more efficiently when the individual system components are able to communicate with at least some others within the system.

REFERENCES

(1) B. D. Greenshields, “A study of traffic capacity,” Proc. Highway Research Board, vol. 14, pp. 448-477, 1935.

(2) K. C. Chu, “Decentralized control of high-speed vehicular strings,” Transportation Science, vol. 8, no. 4, pp. 361 – 384, 1974.

(3) Caudill, R. J. and Garrard, W. L.: Vehicle-Follower Longitudinal Control for Automated Transit Vehicles, J. of Dynamic Systems, Measurement, and Control, December, pp. 241-248 (1977).

(4) P. Seiler, A. Pant, and K. Hedrick, “Disturbance propagation in vehicle strings,” IEEE Transactions on Automatic Control, vol. 49, no. 10, pp. 1835 – 1841, 2004.

(5) J. Zhou and H. Peng, "Range Policy of Adaptive Cruise Control Vehicles for Improved Flow Stability and String Stability," in IEEE Transactions On Intelligent Transportation Systems", Vol. 6, Issue 2, Pages 229-237, June 2005

(6) P. Barooah and J. Hespanha, “Error amplification and disturbance propagation in vehicle strings with decentralized linear control,” in Proceedings of the 44th IEEE Conference on Decision and Control, and the European Control Conference 2005, 2005, pp. 4964–4969.

(7) J. Zhou and H. Peng, "String stability conditions of adaptive cruise control algorithms," in IFAC Symp. on "Advances in Automotive Control", Salerno, Italy, 2004.