An Internetworked Self-Driving Car System-of-Systems

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***Abstract*—This paper presents an overview of the architecture of an internetworked self-driving car system-of-systems. The architecture considers both the car as a system-of-systems as well as multiple cars participation in a larger multi-vehicle system-of-systems. Each relevant aspect of the architecture is reviewed.**

Keywords—self-driving cars; architecture; system-of-systems; autonomy; autonomous vehicle

I. INTRODUCTION

Self-driving cars are posed to create a major change in the way people are transported. They may reduce car ownership with low-cost shared-vehicle services moving from one transport job to the next [1], [2]. For those that choose to still own vehicles, they may make transportation faster, safer and more reliable. They may even allow certain pickup and delivery tasks to be performed without a driver [3]. Current commercially available vehicles offer some automation, such as self-parking [4] and even limited driving in some circumstances [5], [6]. Commercial testing of more fully autonomous vehicles is currently underway [7]. These vehicles, however, must – and are designed to – interact with human-driven vehicles. While human drivers may be common for the foreseeable future, many additional benefits of autonomous vehicles can only be realized through vehicle-to-vehicle coordination.

In the short term, autonomous vehicles may be able to have limited coordination with other autonomous vehicles and specialized roadside devices. As the number of cooperating vehicles grow, the benefits of they provide will as well. The U.S. Department of Transportation and National Highway Traffic Safety Administration have recently (in December of 2016) proposed guidelines and rules for inter-vehicle communications [8]. The use of inter-vehicle communications is designed to facilitate coordination and prevent collisions. In the longer term they can reduce stoplight and stop sign wait times, decrease the need for breaking and acceleration and even reduce travel time.

This paper considers a robust self-driving vehicle system as a system-of-systems. Each vehicle itself brings together multiple systems for system performance. The vehicles then participate in a larger system where their actions are coordinated to produce the aforementioned benefits.

Herein, the architecture for this system is described. First, relevant background material is presented. Then, an overview of the system-of-systems is presented. Finally, individual systems are discussed, before concluding.

II. BACKGROUND

This section presents relevant background work which provides a foundation for the system-of-systems presented herein. First, an overview of prior work on self-driving vehicles is presented. Then, work that has informed the system-of-systems methodology used in this paper is discussed.

A. Self-Driving Vehicles

Self-driving vehicles have been previously considered from a variety of perspectives, all of which are critical to building a successful self-driving car infrastructure. The system must be economically sound: the cost (both financial and, for some, the loss of driving enjoyment) must be outweighed by the benefits of system implementation. From manufacturers' perspectives, the impact on the sale of existing vehicles (which may decline, if vehicles are shared between multiple users) must be considered [2], in addition to competitive factors. For users, the benefit picture is clearer. Economic benefits that may be enjoyed include increased time (from not having to drive), lower operating costs (from the removal of acceleration-breaking cycles due to traffic signals and signs) and increased safety (and the reduction in accident costs).

The public perception [9], [10] of these vehicles must also be considered, as user willingness to adopt is key to widespread system use. Users must trust their self-driving vehicles in order to be willing to use them and systems of building and validating that trust must be – and are (e.g., [11]) being – developed. Questions also abound regarding legal issues, including the ownership of data about user's vehicle operations and liability of a self-driving vehicle gets in an accident.

Technical considerations also abound. Numerous approaches to implementing self-driving capabilities are being considered. Some aim for complete self-operations. Others are considering convoys with a lead car [12] or truck [13] driven by a human. For many of these systems, some form of communication between vehicles will be required. Multiple approaches to this communications system have been proposed [8], [14]; however, for maximum benefit, complete interoperability between all autonomous vehicles is desirable, requiring standardization.

Beyond communications (and even prior to fully connected operations), the vehicles will need path planning [15] that can operate without human intervention, map data to support this path planning and scheduling capabilities to coordinate vehicle operations at various timescales [16]. They will also need robust sensing [17], motion estimation (as GPS and similar systems cannot be solely relied on) [18] and decision making systems. They will also require the ability to learn about everything from user preferences to correcting heuristics used for decision making [19]. Security systems, to prevent conventional, data manipulation and other attacks will also be critical.

Despite the significant technical challenges they pose, interest in the development of autonomous vehicles remains strong. This is likely buoyed by the benefits that can be provided to all prospective vehicle users as well as the benefits that they are poised to provide for numerous special groups such as youth, the handicapped and the elderly [20].

B. *Self-Driving Vehicles as Systems of Systems*

A variety of work has already been done considering self-driving vehicles and multi-vehicle systems from a system-of-systems perspective. Gandhi, Gorod and Sauser [21], for example, have demonstrated how taxi cabs can be modeled in this way. Several system-of-systems approaches to traffic management have been proposed. Critical links have been identified [22] and traffic flow prediction [23] and congestion control [24], [25] techniques have been proposed. The role of the human element is also critical to consider, particularly during the transition period where human-driven and autonomous vehicles must share the road (and at any point where humans can override the system's control). Nadai, et al. [26] discuss how emotion monitoring can help characterize this system component, while Rangra, et al. [27] consider human reliability more broadly.

Key technologies for member systems have also been developed and evaluated in this context. Echegaray and Luo [28] and Kilic, et al. [29] have (separately) developed cruise control systems and Song and Gupta [30] and Rivera, El-Osery and Bruder [31] have (again separately) developed technologies for position and velocity determination.

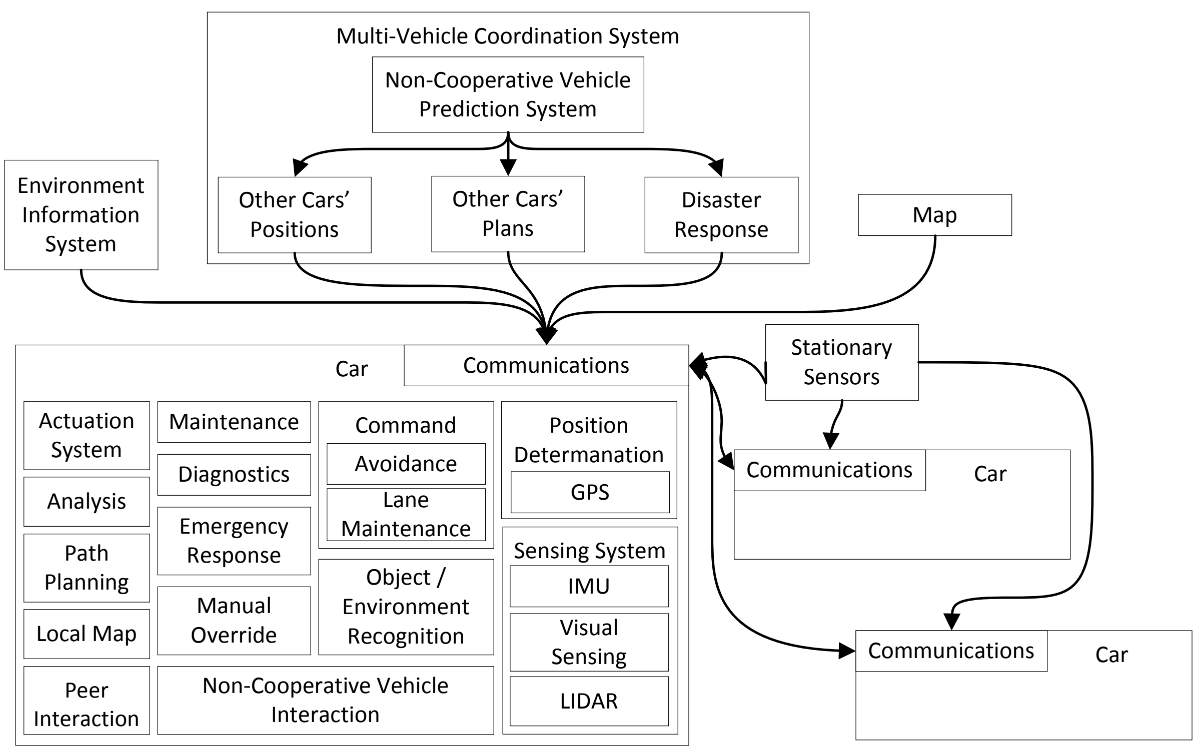

Figure 1. System Overview.

The efficacy of the system-of-systems methodology for safety has also been demonstrated with Coleshill, Ferworn and Stacey [32] showing how it can be used to enhance traffic safety and several studies being performed on its utility for dangerous goods transport [33]–[37].

III. System-of-Systems Overview

This section provides an overview of the entire multi-vehicle system of systems. Figure 1 depicts this system. Sections IV, V and VI provide more details on the three areas of the system-of-systems, the car, the multi-vehicle coordination system and other components, respectively.

The system is comprised of five components. The largest of these components are the multi-vehicle coordination system and the car. The multi-vehicle coordination system is treated as a single large system, despite the fact that it is spread across numerous nodes that provide components of its functionality and functionality across different geographic areas.

The car is arguably the most important component of the system and is able to operate (with diminished functionality) without the other components. It incorporates the hardware and software necessary for unaided autonomous driving. It has fourteen component systems, which are discussed in section IV. The component systems' interoperation is also discussed.

The presence of multiple cars is, of course, expected. Cooperative cars directly communicate with other cooperative cars and exchange information about their locations, intentions and capabilities. The communications module is used for this purpose. Location, intention and capability information is projected, to facilitate decision making, for non-cooperative cars which are present. Cars also use the communications module to communicate with the multi-vehicle coordination system and the components described in the next paragraph.

Three other components are also included in the system-of-systems. These include the environment information system. This system collects, processes, stores and reports on traffic, accidents and weather, roadway and other environmental conditions. This information can be requested for local regions, or for numerous larger regions relevant to a trip (to facilitate weather / traffic / road conditions-aware trip routing). The map component provide relevant map data, again at multiple levels of abstraction and geographic coverage. Finally, stationary sensors collect data regarding and report on localized conditions around the sensor. Stationary sensors may be imbedded into the roadway. Existing sensing platforms (such as those already deployed to collect traffic and road condition information via camera) may be converted to provide data products to self-driving vehicles.

IV. Discussion of System Components - Car

This section provides more detail on each of the car's systems. Each system depicted in Figure 1 is now discussed.

A. Actuation System

This section discusses the actuation system, which is depicted in Figures 2 and 3. This system is responsible for controlling the moving parts which make the car operate.

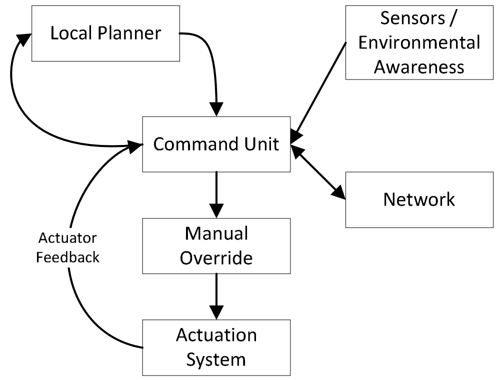

Figure 2. Actuation system in the context of the car systems.

The actuation system has three main pieces: the functional actuation components (wheels, brakes, signals/lights, steering, and airbags), the feedback subsystems for each of these and the control system (including a local processor for making real-time decisions). The system also draws on data inputs from a variety of other sources.

For speed, the emergency response and collision avoidance systems bypass the core command unit, which is more suited to planning routes and processing environmental info.

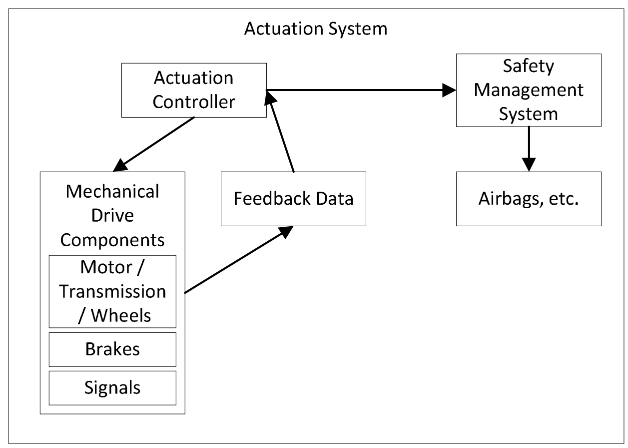

Figure 3. Actuation system.

The manual override also bypasses the command unit and some control functionality to facilitate a human driver taking control, as quickly as possible, if the vehicle malfunctions or in alternate emergency situations.

B. Path Planning

The path planning system, depicted in Figure 4, is responsible for translating user requests into activity plans. This system includes both a global planner that makes long-term plans spanning multiple hours (depending on trip duration and other factors) and a local planner that makes small changes to these global plans to correct for position slippage and based on traffic delays, road closures and other factors.

The system requires inputs including map data, the output from sensors (e.g., IMU, cameras and LIDAR), and car and surrounding object positions information. The system sends its output to the command module. These outputs include needed changes in speed, direction and other actuation capabilities.

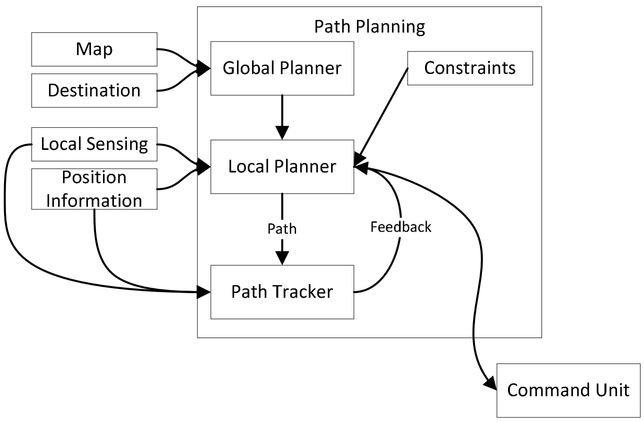

Figure 4. Path Planning System.

C. *Position Determanation*

The position determination and localization system for the autonomous car architecture is made up of several subsystems. These include the GPS hardware and software and a processing system using a Kalman filter and other algorithms for determining position (in particular for in cases where the GPS may be unavailable or providing questionable data). The system uses data collected from the sensing system (such as its IMU) and information from the actuation system's feedback data. The system provides position and velocity information to the command and other systems within the car.

D. *Emergency Response*

The emergency response system provides the car's capability for reaction to the unexpected, including dealing with erratic drivers and obstacles. Principally, the approach to dealing with emergency situations is to take immediate evasive action, as needed, and perform system checkout (if any trigger, such as leaving the roadway or an impact is detected). If the vehicle is not impaired, the path planning system is tasked with finding a new route from the vehicle's current position. For any situation, beyond the most basic on-road avoidance, the vehicle's passenger (or stand-by human driver) is notified. In many cases, the system seeks to bring the vehicle to a stop in a safe location (e.g., if any impact or other issue is detected).

Dealing with an erratic driver can be a more pronounced challenge, as it may persist over a period of time. Several choices are considered by the system. These include stopping the vehicle, finding a new path, backing off and/or alerting the human driver/passenger. In most cases, the identification of the erratic driver is communicated to other cars and vehicle coordination systems on the network. These response options are not mutually exclusive and a plan may incorporate several.

E. *Analysis*

This system takes in large amounts of data and processes it into useful information that other systems can use. In addition to providing software modules to deal with cross-system data analysis challenges, it also controls processor time that can be requested for intensive processing by other units. To support the production of data products that are used by multiple systems, the analysis system is connected to and receives information from the communications and sensing systems.

F. *Maintainence & Diagnostics*

There are two different systems within both the maintenance and diagnostics systems, which are depicted in Figure 5. One handles computational and software (C&S) aspects and the other handles the physical components.

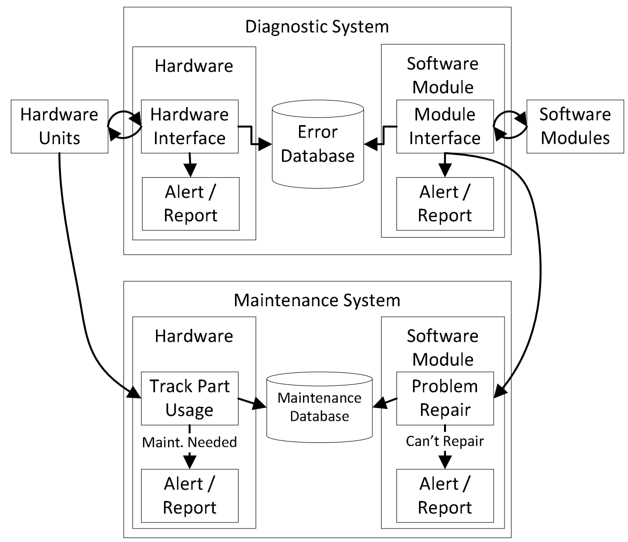

Figure 5. Diagnostic and Maintenance Systems.

The C&S components are monitored through a digital diagnostic system which tracks inputs and output of all systems to ascertain as to if they are functioning properly. The physical system tracks the physical components like the actuators, tires and gas. Data is communicated to a central system, for correlation with manufacturer service recommendations and potentially even service scheduling. A local assessment system also detects critical-level issues.

G. *Command*

The command system is in charge of overall vehicle operations. This includes making decisions based on the input of other systems as well as making high-level driving decisions. It also, in conjunction with the analysis module, coordinates system-spanning activities. For example, for lane following and overtaking another vehicle (for which it uses the communications, environment information, sensing and actuation systems), it determines (using the analysis and path planning systems) a path and starts (using the actuation system) the car moving forward. Similarly, for parking (of a vehicle without a passenger) it identifies parking spaces, determines the sufficiency of open spaces for parking and identifies the best available spot and commands the actuation system to have the car proceed with parking.

H. *Communications*

Car systems communicate with other cars and the multi-vehicle coordination system through this system. A variety of mediums are used, if available, including Wi-Fi, radio and cellular networks.

I. Object & Environment Recognition

The object and environment recognition system uses a neural network that is trained to detect traffic signs, pedestrians and other common surroundings. Training data includes imagery collected under varying weather and other conditions.

J. Manual Override

This system provides a sensor for entering a manual override mode which changes command from the command system to the user. The actuation system is still involved in translating user input into control instructions. The manual override is digital hardware (not software) to ensure reliability.

K. Local Map

The local map system stores a local copy of information from the larger map. This supports non-connected operations.

L. Peer Interaction

The peer interaction module communicates with other nearby vehicles. Activities are coordinated and data is shared.

M. Sensing System

The sensing system collects information for use by other systems. IMU, optical, traffic and road data is collected.

N. Non-Cooperative Vehicle Interaction

The non-cooperative vehicle interaction system is responsible for aiding the planning system by projecting the actions and impact of decisions by non-cooperative vehicles (which do not share their information). This would include human-driven vehicles and those that (due to defect or other reason) are not transmitting this information.

V. Discussion of System Components – Multi-Vehicle Coordination System

This section discusses the multi-vehicle coordination system. This is a server-based system that provides information to individual cars and coordinates their activities.

A. Other Cars' Plans Determanation

This system collects information from cooperative vehicles about their objectives and plans for achieving them. This information is used for coordination purposes and provided (in aggregate form) to other cooperative vehicles for planning.

B. Other Cars' Positions Determanation

This system collects position information from cooperative vehicles about their current location. It also collects sensed data from cooperative vehicles about the presence and location of non-cooperative vehicles. This information is provided (in aggregate) to other cooperative vehicles for planning purposes.

C. Disaster Response

The disaster response system is the multi-vehicle coordination system equivalent of the on-car emergency response system. This system is invoked with a collision or other emergency exceeds a (configurable) threshold impact level. It coordinates response, road closures and rerouting.

D. Non-Cooperative Vehicle Prediction System

This system is the equivalent of the on-vehicle system for predicting the actions of non-cooperative vehicles. It collects information about these vehicles from cooperative cars, uses it for planning cooperative vehicle coordination and provides it to other cooperative vehicles.

VI. Discussion of Other System Components

This section covers components that are not part of the car or multi-vehicle coordination systems. The environment information, stationary sensor and map systems are discussed.

A. Environment Information System

The environment information system, depicted in Figure 6, provides information about the local and extended conditions which are relevant to the trip. The system receives prospective route information from the path planning module to allow it to provide relevant long-range information. It also updates local conditions based on actuator feedback and local sensing.

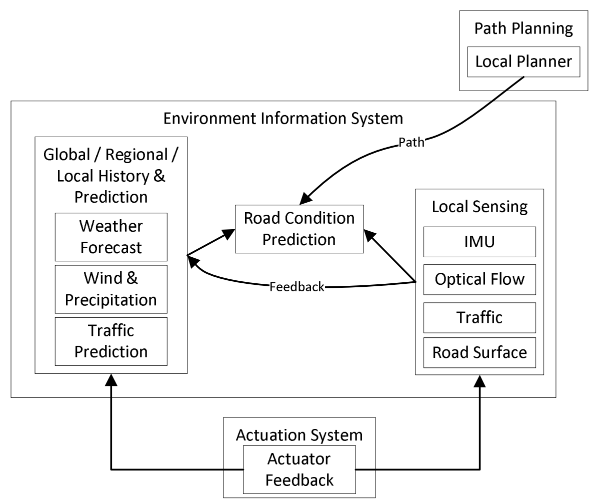

Figure 6. Environment Information System.

B. Stationary Sensors

Stationary sensors collect data on local conditions around the sensor. Existing sensing platforms may be converted to provide data products to self-driving vehicles. These data products may be provided to the vehicles directly or may be accessed through the internet (via Wi-Fi or cellular networks).

C. Map

The map system, which is separated from the multi-vehicle coordination system to allow use of multiple providers' data, provides cars map data. In addition to enabling provider selection, data sets can be combined for map-spanning trips.

VII. Conclusions & Future Work

This paper has provided an overview of the two core system components (the car and the multi-vehicle coordination system) and the system-member systems. Future work will need to consider other key areas of system design and implementation including abstraction, application space versus real-time processing considerations, maintenance for the multi-vehicle coordination system (in particular, the pruning of stale information) and system security. The interaction of the core car systems with optional enhancement features (which will likely be commonly added by car manufacturers), such as remote starting and door locking/unlocking, car location and ride-sharing capabilities, is also a topic for future work.

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References

[1] T. Litman, "Autonomous Vehicle Implementation Predictions," in *2014 Transportation Research Board Annual Meeting*, 2014, pp. 14–6525.

[2] B. Schoettle and M. Sivak, "Potential impact of self-driving vehicles on household vehicle demand and usage," 2015.

[3] S. Hyken, "Four Ways Self-Driving Cars Will Improve Customer Service," *Forbes*, 25-Feb-2017.

[4] M. Brown, "Tesla Autopilot's Latest Update Has Autonomous Parallel Parking | Inverse," *Inverse*, 24-Feb-2017.

[5] R. Duffer, "Tesla Model X P100D sets autopilot to a fast future - Portland Press Herald," *Portland Press Herald*, 17-Feb-2017.

[6] L. Mearian, "Here's why self-driving cars may never really be self-driving | Computerworld," *Computerworld*, 23-Feb-2017.

[7] T. Seppala, "Google's self-driving cars are getting better at autonomy," *Engadget*, 02-Feb-2017.

[8] National Highway Traffic Safety Administration, "U.S. DOT advances deployment of Connected Vehicle Technology to prevent hundreds of thousands of crashes | NHTSA," *NHTSA Website*, 2016. [Online]. Available: https://www.nhtsa.gov/press-releases/us-dot-advances-deployment-connected-vehicle-technology-prevent-hundreds-thousands. [Accessed: 25-Feb-2017].

[9] B. Schoettle and M. Sivak, "A survey of public opinion about autonomous and self-driving vehicles in the U.S., the U.K., and Australia," 2014.

[10] D. Howard and D. Dai, "Public Perceptions of Self-driving Cars: The Case of Berkeley, California," in *93rd 40 Annual Meeting of the Transportation Research Board*, 2013.

[11] M. Wagner and P. Koopman, "A Philosophy for Developing Trust in Self-driving Cars," Springer, Cham, 2015, pp. 163–171.

[12] A. Wright and Alex, "Automotive autonomy," *Commun. ACM*, vol. 54, no. 7, p. 16, Jul. 2011.

[13] M. McFarland, "When truck drivers tailgating is actually a good thing - Feb. 16, 2017," *CNN Tech*, 2017. [Online]. Available: http://money.cnn.com/2017/02/16/technology/truck-platoons-peloton-omnitracs/. [Accessed: 26-Feb-2017].

[14] S. Narla, "The Evolution of Connected Vehicle Technology: From Smart Drivers to Smart Cars to... Self-Driving Cars," *Inst. Transp. Eng. J.*, vol. 83, no. 7, pp. 22–26, 2013.

[15] U. Lee, S. Yoon, H. Shim, P. Vasseur, and C. Demonceaux, "Local path planning in a complex environment for self-driving car," in *The 4th Annual IEEE International Conference on Cyber Technology in Automation, Control and Intelligent*, 2014, pp. 445–450.

[16] J. Kim, H. Kim, K. Lakshmanan, and R. (Raj) Rajkumar, "Parallel scheduling for cyber-physical systems," in *Proceedings of the ACM/IEEE 4th International Conference on Cyber-Physical Systems - ICCPS '13*, 2013, p. 31.

[17] Gim Hee Lee, F. Fraundorfer, and M. Pollefeys, "Structureless pose-graph loop-closure with a multi-camera system on a self-driving car," in *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2013, pp. 564–571.

[18] G. Hee Lee, F. Faundorfer, and M. Pollefeys, "Motion Estimation for Self-Driving Cars with a Generalized Camera," in *The IEEE Conference on Computer Vision and Pattern Recognition*, 2013, pp. 2746–2753.

[19] M. Bojarski *et al.*, "End to End Learning for Self-Driving Cars," Apr. 2016.

[20] J. Yang and J. F. Coughlin, "In-vehicle technology for self-driving cars: Advantages and challenges for aging drivers," *Int. J. Automot. Technol.*, vol. 15, no. 2, pp. 333–340, Mar. 2014.

[21] S. J. Gandhi, A. Gorod, and B. Sauser, "A case study: The New York City yellow cab System of Systems," in *2011 6th International Conference on System of Systems Engineering*, 2011, pp. 282–287.

[22] G. Ibarra and J. T. Stracener, "A System of Systems' Prospective for Determining the Highway Systems Critical Links," in *2007 IEEE International Conference on System of Systems Engineering*, 2007, pp. 1–6.

[23] L. Chen and C. L. P. Chen, "Ensemble Learning Approach for Freeway Short-Term Traffic Flow Prediction," in *2007 IEEE International Conference on System of Systems Engineering*, 2007, pp. 1–6.

[24] A. Ferrara, A. NaiOleari, S. Sacone, and S. Siri, "Freeway networks as Systems of Systems: An event-triggered distributed control scheme," in *2012 7th International Conference on System of Systems Engineering (SoSE)*, 2012, pp. 197–202.

[25] C. E. Dickerson, S. Ji, and R. Roslan, "Formal methods for a system of systems analysis framework applied to traffic management," in *2016 11th System of Systems Engineering Conference (SoSE)*, 2016, pp. 1–6.

[26] S. De Nadai *et al.*, "Enhancing safety of transport by road by on-line monitoring of driver emotions," in *2016 11th System of Systems Engineering Conference (SoSE)*, 2016, pp. 1–4.

[27] S. Rangra, M. Sallak, W. Schon, and F. Vanderhaegen, "On the study of human reliability in transportation systems of systems," in *2015 10th System of Systems Engineering Conference (SoSE)*, 2015, pp. 208–213.

[28] S. Echegaray and Wenbin Luo, "The modular design and implementation of an intelligent cruise control system," in *2008 IEEE International Conference on System of Systems Engineering*, 2008, pp. 1–6.

[29] I. Kilic, A. Yazici, O. Yildiz, M. Ozcelikors, and A. Ondogan, "Intelligent adaptive cruise control system design and implementation," in *2015 10th System of Systems Engineering Conference (SoSE)*, 2015, pp. 232–237.

[30] J. Song and S. Gupta, "SLAM based shape adaptive coverage control using autonomous vehicles," in *2015 10th System of Systems Engineering Conference (SoSE)*, 2015, pp. 268–273.

[31] R. Rivera, A. I. El-Osery, and S. Bruder, "Leveraging wireless communication systems for aiding inertial-based navigation systems," in *2015 10th System of Systems Engineering Conference (SoSE)*, 2015, pp. 158–163.

[32] E. Coleshill, A. Ferworn, and D. Stacey, "Traffic Safety using Frame Extraction Through Time," in *2007 IEEE International Conference on System of Systems Engineering*, 2007, pp. 1–5.

[33] S. De Nadai, F. Parodi, and D. Pizzorni, "A system of systems approach to near miss accidents in dangerous goods road transportation," in *2012 7th International Conference on System of Systems Engineering (SoSE)*, 2012, pp. 219–222.

[34] L. Zero, C. Bersani, R. Sacile, and M. H. Laarabi, "Bi-objective shortest path problem with one fuzzy cost function applied to dangerous goods transportation on a road network," in *2016 11th System of Systems Engineering Conference (SoSE)*, 2016, pp. 1–5.

[35] C. Roncoli, R. Sacile, and M. G. H. Bell, "Operational and real decision problems in the risk-averse transportation of dangerous goods by road," in *2012 7th International Conference on System of Systems Engineering (SoSE)*, 2012, pp. 209–213.

[36] C. Bersani and C. Roncoli, "Real-time risk definition in the transport of dangerous goods by road," in *2012 7th International Conference on System of Systems Engineering (SoSE)*, 2012, pp. 131–136.

[37] M. Benza *et al.*, "Intelligent Transport Systems (ITS) applications on dangerous good transport on road in Italy," in *2012 7th International Conference on System of Systems Engineering (SoSE)*, 2012, pp. 223–228.