Development of an Integrated Transportation System of Connected Automated Vehicles and Highways

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Tremendous efforts have been made in the field of vehicle automation. That is, developing advanced sensors and algorithms that are installed on vehicles to imitate or eventually transcend the complexity of human drivers. This approach focuses solely on vehicle-based technologies and takes the road as the status quo. Many players are investing in this vehicle-based approach, from giant high-tech companies and car manufacturers, to small start-ups, by taking advantage of the latest development in hardware, software, and communication technologies. Despite the significant progress that has been made, automated vehicles are still not safe and reliable enough for large scale deployment, as indicated by incidents during automated vehicle testing.[1,2]

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Self-Driving Cars: A Vehicle-based Approach for Automated Driving

According to the 2018 *Gartner Hype Cycle for Emerging Technologies* report, automated driving still has more than 10 years to reach the "Plateau of Productivity."[3] Although Waymo just launched the first commercial self-driving taxi service, Waymo CEO John Krafcik said, "Self-driving cars will require driver assistance for many years to come," and "the technology is 'really, really hard.'"[4] The CEO of the Toyota Research Institute Gill Pratt said at the 2019 Consumer Electronics Show, "Now, none of us in the automobile or IT industries are close to fully answering these questions."[5]

The major challenges for automated vehicles include: a) sensing the environment, b) understanding human intents, and c) the resulting high cost. Sensing, or situation awareness, is a critical component for automated driving. A typical automated vehicle relies on a range of different sensors, including but not limited to LiDAR (light detection and ranging), radar, cameras, and ultrasonic. Those sensors are used to cover different ranges to detect the environment and moving objectives about the vehicle. Advanced artificial intelligence (AI) algorithms are developed and deployed on the vehicle to make sense of the data streams from those sensors. The AI algorithms are also supposed to learn from the human drivers' behavior and figure out how to drive the vehicle and how to interact with everything around it. What makes it more complicated is that automated vehicles also need to learn how to interact with each other, especially among vehicles from different manufacturers.

All those sensors and software/hardware are making the cost of self-driving vehicles currently beyond the affordable range of most people, not to mention the millions of mileage needed to train AI algorithms.[6] It is also worth noting that onboard computing and communication systems consume significant power.[7] According to a recent study of connected and automated vehicles (CAVs), vehicle primary energy use could increase "by 3–20 percent due to increases in power consumption, weight, drag, and data transmission."[8] The situation would be even worse for electric cars, with driving range being one of the major obstacles for its general market adoption.

How Intelligent Infrastructure Can Help

The modern highways originated in the early 20th century in response to the rapidly increasing use of the modern automobile. Although standards have not been developed for the next generation road infrastructure, there have been discussions for several years calling for roadway standards that better serve the needs of automated vehicles.[1,9-12] It is understood that deliberately designed roadway infrastructure can make the deployment of smart vehicles occur faster, more effectively, and at a lower cost.

The Infrastructure Sees Better. One of the major challenges for automated driving is sensing the environment. For example, vehicles traveling at a medium to high speed have a small amount of time to detect, process, and identify objects, whether a pedestrian or a pile of snow. One issue is that vehicle sight lines are often blocked by other vehicles in the vicinity. On the contrary, a sensor mounted near the roadside has the luxury of time to track a pedestrian from the second it enters the detection range to the second it leaves. Moreover, the sensor can be mounted high to cover a wide range of road without sight obstructions.

The Infrastructure Knows its Turf the Best. Although automated vehicle testing is accumulating millions of miles, each mile of the road has only been "learned" by a limited number of times, which is only a small percentage of its full 24/7 situations. On the contrary, the roadside sensors are at fixed locations, monitoring their limited detection range 24/7. Data of all possible situations about traffic and the environment from this limited range are accumulated very fast, making mastering their "turf" a much easier task. Putting all the knowledge from the roadside sensors together results in an expert system for the network, including every vehicle, whether smart or not, whether self-driving or driverless, which is still improving using artificial intelligence algorithms taking advantage of the continuous data feeds.

The Infrastructure Reduces the Burden on Vehicle. In the vehicle-based approach, the vehicle itself has to bear the burden of carrying not only a superset of sensing devices, but also a supercomputer to process and learn the entire roadway while traversing at relatively high speed. However, if infrastructure-based sensors and processors can see and know the roadway, automated vehicles can rely on this infrastructure-based data to assist with a significant portion of the automated driving task. In this way, automated vehicles do not need as extensive of an extremely complex onboard system. Such vehicles would have a much lower cost.

Infrastructure as a Coordinator for Automated Vehicles. It can be expected that there will be automated vehicles at different automation levels, by different manufacturers, traveling on the roads. The problem of traffic control is expanded to the entire road network—not to mention that there will be a significant period of time when automated vehicles share the road with vehicles driven by humans. The road infrastructure in this context would be the best coordinator to control and manage the homogenous travel flow.

Additional Layer for Safety and Reliability. Automated driving system failure is a significant concern. Equipping the road infrastructure with equivalent intelligence and sharing the vehicle control burden with automated vehicles provides an additional layer of system reliability. Proving this redundancy in the system creates better system safety and reliability than either of the infrastructure and vehicle itself.

Low Cost on Vehicle and Overall Investment. An estimate for the comparison of investment (COI) ratio between total societal investment for the vehicle-based and connected automated vehicle highway (CAVH) approaches done by the team at the University of Wisconsin-Madison in Wisconsin, USA overwhelmingly shows in favor of the CAVH approach in all scenarios, ranging from more than 100:1 to 2000:1 by different roads and metropolitan areas.[13] The next section explains the CAVH approach. An included sensitivity analysis regarding the market penetration shows that the CAVH approach is more cost-effective than the vehicle-based approach when more than 0.62-2.0 percent (varying by scenario) of the vehicles are in automated driving mode.

Towards a System Orientated Design: Connected Automated Vehicle Highway Systems

Transportation is a complex system, involving physical entities (people, vehicles, road infrastructure), and policy and service such as communication and traffic operations and management strategies. In this context, we propose a system-oriented design towards automated driving: CAVH systems. Technical details are available from two filed patent applications.[14-15] The CAVH approach emphasizes the automation of the road infrastructure and transportation system integration. Specifically, the key points of CAVH include:

Multidimensional Consideration

The CAVH approach aims to cover all the major elements of transportation systems in a multidimensional perspective. Figure 1 shows a three-dimension view of it: Connectivity, Vehicle Automation, and System Integration.

The three dimensions in Figure 1 can be defined using different levels, similar to the SAE vehicle automation levels:[16]

- **Vehicle automation.** This dimension represents the intelligence of vehicles, and levels are from the SAE vehicle automation level definitions;
- **Connectivity.** The dimension of connectivity is to present information flows, measured in terms of volume and content. Specifically, five levels are defined:
    - **C0: No connectivity.** Both vehicles and travelers do not have access to any traffic information;
    - **C1: Information assistance.** Vehicles and travelers can only access aggregated traffic information of certain accuracy, resolution, and noticeable delays, such as average traffic speed at the downstream traffic detection station five minutes ago;
    - **C2: Limited connected sensing.** Vehicles and travelers can access live traffic information of high accuracy and unnoticeable delay, through connection with roadside units, other vehicles, and other information providers. However, the information may not be complete;
    - **C3: Redundant information sharing.** Vehicles and travelers are provided with information of adequate accuracy and almost in real time from multiple sources. The information available is complete but redundant with different formats due to the various sources;

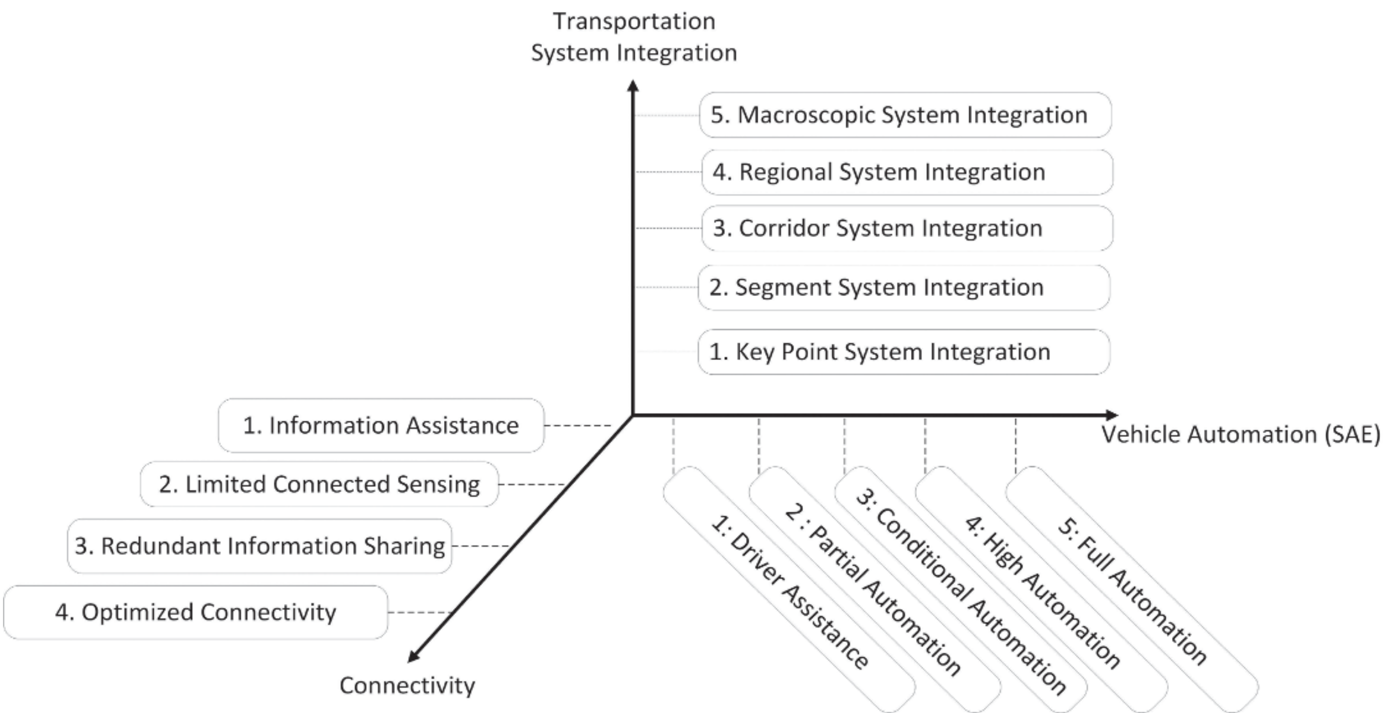

Figure 1. The three dimensions of the CAVH approach.

- C4: **Optimized connectivity.** Information from various sources is integrated, completed, and unified before provided to vehicles and travelers.

- **Transportation System Integration.** This dimension represents the scale of system coordination and optimization. Specifically, six levels are defined:
  - **S0: No integration.** There is no traffic control and management measures for coordination or optimization, such as pre-timed traffic signals.
  - **S1: Key point system integration.** Traffic control measures are covering a small area such as actualized signals at intersections and ramp metering, and those measures are only for the major travel mode, such as passenger cars;
  - **S2: Segment system integration.** The measures are extended to a short road segment such as a freeway segment between two ramp access points, and for most of the travel modes, such as passenger cars and buses;
  - **S3: Corridor system integration.** The measures are extended to a corridor with connecting roads and ramps, and for all coexisting traffic modes, such as integrated corridor management;
  - **S4: Regional system integration.** The scale of coordination and optimization now covers a city or urban area for both normal conditions and under emergency or incident; and
  - **S5: Macroscopic system integration.** The scale of coordination and optimization now covers several regions and inter-regional traffic.

Redistribution of Driving Tasks. Driving a vehicle safely from the origin to the destination involves essential activities or "driving tasks," which can be categorized as Control, Guidance, and Navigation.[17] In the context of a CAVH system, the driving tasks, instead of relying solely on vehicles' capabilities, are redistributed. To simplify the following discussion, we define all roadside units and traffic control/management centers as an Intelligent Road Infrastructure System (IRIS), which is a subsystem under CAVH.[15]

Figure 2 shows an exemplary distribution of driving tasks of CAVH. The IRIS Subsystem and Vehicle Subsystem jointly cover all the driving tasks among the three performance levels. The two subsystems both have sensing and telecommunication capabilities to facilitate in those driving tasks, and the two subsystems are highly integrated to work together through the two types of capabilities. The integration and collaboration of the vehicle and IRIS subsystems also provide the redundant backup for each other, which increases the overall safety and reliability.

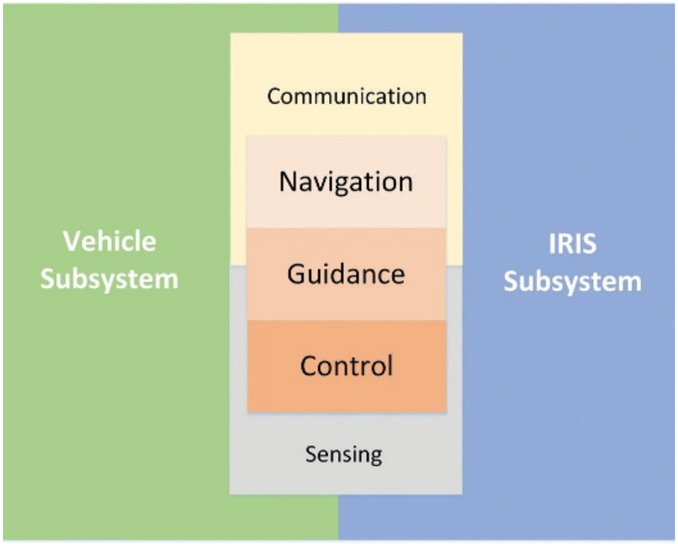

Figure 2. Redistribution of driving tasks.

A Server-Client Example

One way to look at the CAVH approach is through the analogy of a client-server relationship, with vehicles as the clients and infrastructure as the server. The vehicle-based approach aims at developing super smart vehicles with limited consideration and requirements for the road infrastructure and other transportation system components. In other words, the vehicle-based approach is designed to be a fat client–thin server mode. The CAVH approach, however, can facilitate the thin client–fat server mode, as shown in Figure 3, in which the vehicles receive and follow detailed instructions from the IRIS, similar to a railway system.

To realize this thin client–fat server mode, a well-instrumented infrastructure would be needed. One design is shown in Figure 4, *in* which: 1) roadside units (RSUs) are deployed on the roadside to monitor the vehicles and communicate with them, and 2) traffic control units (TCUs) and traffic control centers (TCCs) do the heavy lifting to generate real-time instructions for vehicles.

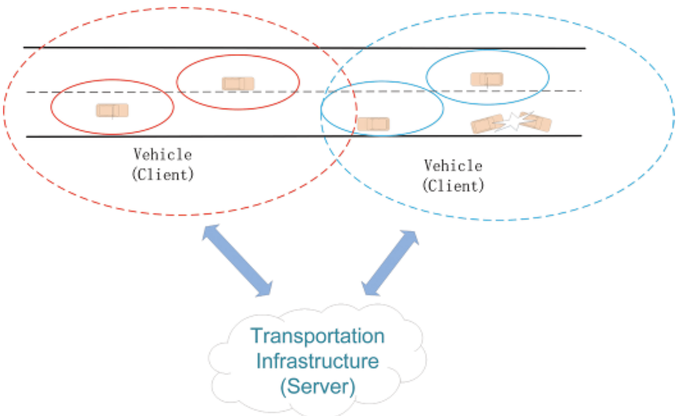

Figure 3. CAVH server-client model.

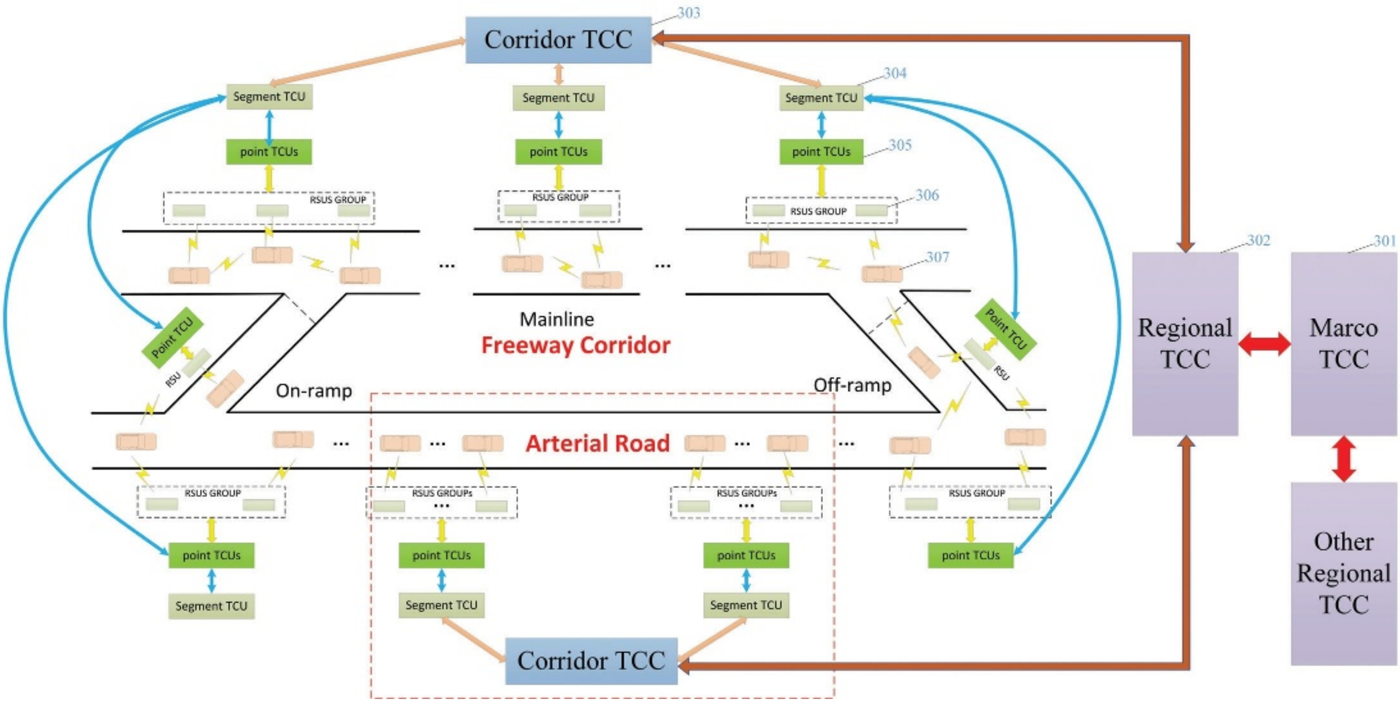

Figure 4. CAVH managing a corridor.

Conclusions

To achieve automated driving, tremendous efforts have been undertaken to make vehicles smarter. These efforts have mostly focused on improvements to vehicles and very little on advances related to road infrastructure. Although there has been significant progress, this approach still has a long way to go before automated vehicles are safe and reliable enough for largescale deployment.[3-5] It becomes more and more clear that a well-instrumented road infrastructure can help overcome the difficulties in automated driving. That is, the road should be smart too when the vehicles are smart, but not smart enough.

In this article, a systematic approach to automated driving, the CAVH approach, is proposed. Instead of focusing solely on making vehicles smart, the CAVH approach emphasizes seamless collaboration of smart vehicles and smart infrastructure in the transportation system context. The CAVH approach covers all aspects of the transportation system in three dimensions: 1) vehicle–vehicle automation, 2) infrastructure–connectivity, and 3) system–system integration. CAVH can facilitate the evolution and growth of all related automated driving technologies and industries, and ultimately become an eco-system for "Smart Vehicle, Smart Road, and Intelligent System."

The CAVH system is not a competitor against automated vehicles, but a facilitator that can speed up the deployment of automated vehicles. A smart road infrastructure and a smart transportation system built upon it can help vehicles deal with substantial technical and reliability challenges due to the complexity of driving tasks and the dynamic road environment with a higher overall benefit-cost ratio. This CAVH system supports proactive and reactive safety strategies on both the vehicle and roadside, providing additional layers of system redundancy and backup. It is also a natural smart city platform upon which other applications and systems can be built. **itej**

References

1. Knight, W. "Tesla Crash Will Shape the Future of Automated Cars." *MIT Technology Review*, July 1, 2016. https://www.technologyreview.com/s/601829/tesla-crash-will- shape-the-future-of-automated-cars [Accessed October 7, 2019]
2. Grossman, A. "Three Takeaways from NTSB's Preliminary Report on the First Fatal Automated Vehicle Crash." Eno Center for Transportation, May 31, 2018. https://www.enotrans.org/article/three- takeaways-from-ntsbs-preliminary-report-on-the-first-fatal-automated-vehicle-crash [Accessed October 7, 2019]
3. Panetta, K. "5 Trends Emerge in the Gartner Hype Cycle for Emerging Technologies." Gartner, August 16, 2018. https://www.gartner.com/smarterwithgartner/5-trends-emerge-in-gartner-hype-cycle-for-emerging-technologies-2018 [Accessed October 7, 2019]
4. Gurman, M. "Waymo CEO Says Self-Driving Cars Won't Be Ubiquitous for Decades." Bloomberg, November 13, 2018. https://www.bloomberg.com/news/articles/2018-11-13/waymo-ceo-says-self-driving-cars-won-t-be-ubiqitious-for-decades. [Accessed October 7, 2019]

5. Pratt, G. "2019 International CES – Remarks." Toyota USA Newsroom, January 8, 2019. https://global.toyota/en/newsroom/corporate/26085202.html [Accessed October 7, 2019]
6. Welch, D. and Behrmann, E. "Who's Winning the Self-Driving Car Race?" Bloomberg, May 7, 2018. https://www.bloomberg.com/news/features/2018-05-07/who-s-winning-the-self-driving-car-race [Accessed October 7, 2019]
7. Stewart, J. "Self-Driving Cars Use Crazy Amounts of Power, and It's Becoming a Problem." *Wired*, February 6, 2018. https://www.wired.com/story/self-driving- cars-power-consumption-nvidia-chip [Accessed October 7, 2019]
8. Gawron, J.H.; Keoleian, G.A.; De Kleine, R.D.; Wallington, T.J.; and Kim, H.C. "Life Cycle Assessment of Connected and Automated Vehicles: Sensing and Computing Subsystem and Vehicle Level Effects." Environmental Science & Technology, 2018. 52(5):3249-56.
9. Kaplan, J. "Roads That Work for Self-Driving Cars," *Wall Street Journal*, July 8, 2016. https://www.wsj.com/articles/roads-that-work-for-self-driving-cars-1467991339 [Accessed October 7, 2019]
10. Ng, A. and Lin, Y. "Self-Driving Cars Won't Work Until We Change Our Roads—And Attitudes." *Wired,* March 15, 2016. https://www.wired.com/2016/03/self-driving-cars-wont- work-change-roads-attitudes [Accessed October 7, 2019]
11. McCauley, R. "How Infrastructure Disrepair Is Holding Back Autonomous Vehicles." GOVERNING, April 5, 2017. http://www.govtech.com/fs/How-Infrastructure-Disrepair- is-Holding-Back-Autonomous-Vehicles.html [Accessed October 7, 2019]
12. Oliver, N.; Potočnik, K.; and Calvard, T. "To Make Self-Driving Cars Safe, We Also Need Better Roads and Infrastructure." *Harvard Business Review*, August 14, 2018. https://hbr.org/2018/08/to-make-self-driving-cars-safe-we-also-need-better-roads-and- infrastructure [Accessed October 7, 2019]
13. Ran, B.; Cheng, Y.; Zhang, Z.; and Dong, S. "Preliminary Comparisons of Investment for Infrastructure-based (System-based) Automated Driving vs. Vehicle-based Automated Driving." Report No. 20180225, TOPS Lab, University of Wisconsin at Madison, 2018.
14. Ran, B.; Cheng, Y.; Li, S; Ding, F.; Jin, J.; Chen, X.; and Zhang, Z. "Connected Automated Vehicle Highway Systems and Methods." US Patent Application No. 15/628,331, 2018.
15. Ran, B.; Cheng, Y.; Li, S; Zhang, Z.; Ding, F.; Tan, H.; Wu, Y.; Dong, S.; Ye, L.; Li, X.; Chen, T.; Shi, K.; Jin, J.; and Chen, X. "Intelligent Road Infrastructure System (IRIS): Systems and Methods." US Patent Application No. 16/135,916, 2019
16. "International S. Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles." SAE International, 2018.
17. Lunenfeld, H. and Alexander, G.J. "A user's guide to positive guidance *(3rd Edition)*." FHWA SA-90-017: Federal Highway Administration, Washington, DC, 1990.

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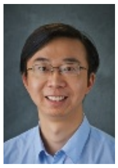

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