Mobility Control Technology for Safe, Comfortable, and Efficient Mobility and Transportation

Control of autonomous driving is a key technology for mobility systems that deliver friction-free movement, overcoming the societal challenges posed by the shortage of drivers in the transportation industry and the human and economic costs of traffic accidents. Along with the vehicle's own sensing and improvements in autonomous driving performance and reliability, this control also needs to interoperate with other vehicles and infrastructure systems if it is to be deployed in transportation systems that operate in urban environments where corners and intersections are common. This article presents examples of what Hitachi is doing to make this possible, describing dynamics control for platooning vehicles that combines safety and comfort with efficiency, traffic flow control for intersections, and graceful degradation design techniques that enhance the reliability of mobility automation itself.

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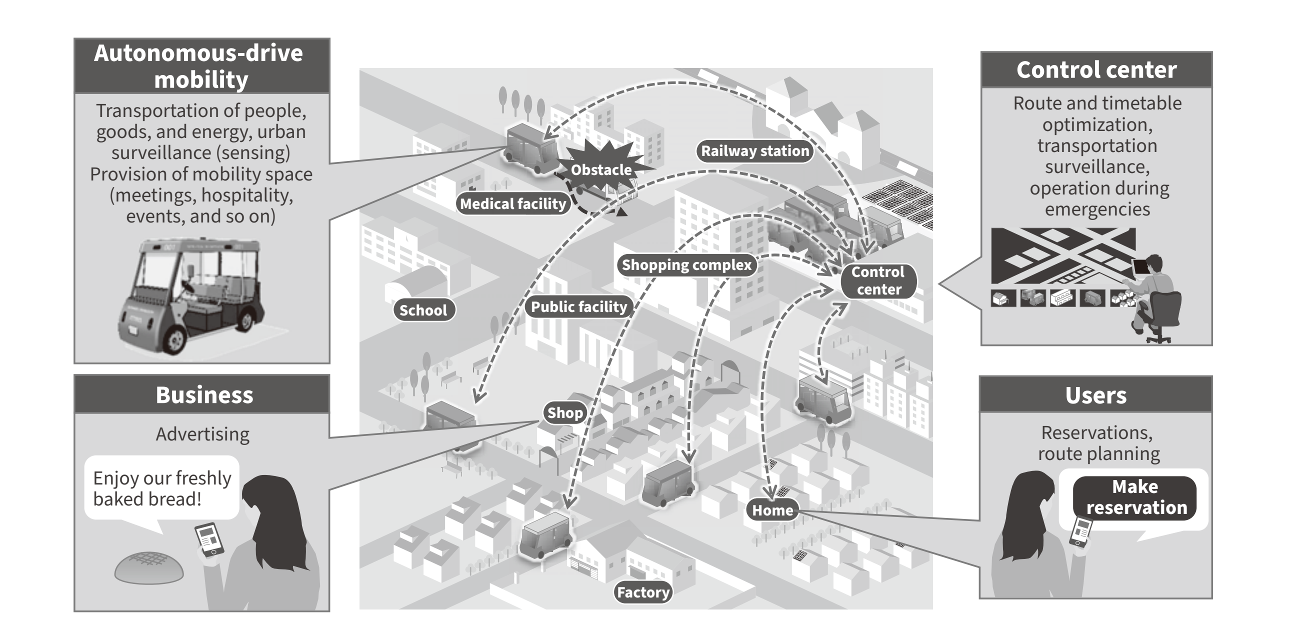
1. Introduction

Enhancements to safety and comfort have long been important vehicle performance criteria, with particular progress being made on the development and application of autonomous driving to reduce traffic accidents caused by driver error. By eliminating any driver input, autonomous driving will not only reduce the number of accidents caused by human error, it is also the driving force behind a major shift in how people get from place to place, changing the very nature of vehicles through the provision of driverless mobility. This has led to IT vendors and other companies from outside the automotive industry launching trials and exploring the potential of new mobility businesses that use autonomous driving. It has also caused vehicle manufacturers to consider a shift away from their traditional business models based on vehicle sales, looking instead to become mobility service providers.

Figure 1 shows examples of services that use autonomous-drive mobility. This involves managing operations from a control center that consolidates information on users, providers, and autonomous-drive mobility and makes it available as appropriate. It also means that autonomous-drive mobility has the potential to serve as more than just a means of regional mobility and transportation. Rather, it will also play a key role in linking local businesses and consumers together by serving as a means of transmitting information. Implementing such mobility services will require a wide variety of technologies. These include the supervisory control needed to operate autonomous-drive mobility, remote control for avoiding situations where operation is brought to a halt by unexpected obstacles, reliable and secure communications between the control center and autonomous-drive mobility systems, and autonomous driving control techniques that feature interoperation with supervisory control and other vehicles. Given its direct implications for both safety and user comfort, the control of autonomous driving is particularly important for the practical rollout of friction-free mobility systems.

Figure 1 — Mobility Services Using Autonomous-drive Mobility

Autonomous-drive mobility can serve many roles beyond just being a means of transportation, including urban sensing and acting as an information interface between local residents and businesses.



2. Control Techniques for Safe, Comfortable, and Efficient Mobility and Transportation

The following sections present examples of work by Hitachi on the practical implementation of autonomous driving that can provide safe, comfortable, and efficient transportation, even in urban environments where corners and intersections are common. These include dynamics control for platooning vehicles that combines safety and comfort with efficiency, traffic flow control for intersections, and graceful degradation design techniques that enhance the reliability of mobility automation itself.

2. 1 Dynamics Control of Platooning for Both Safety and Comfort and Efficient Transportation

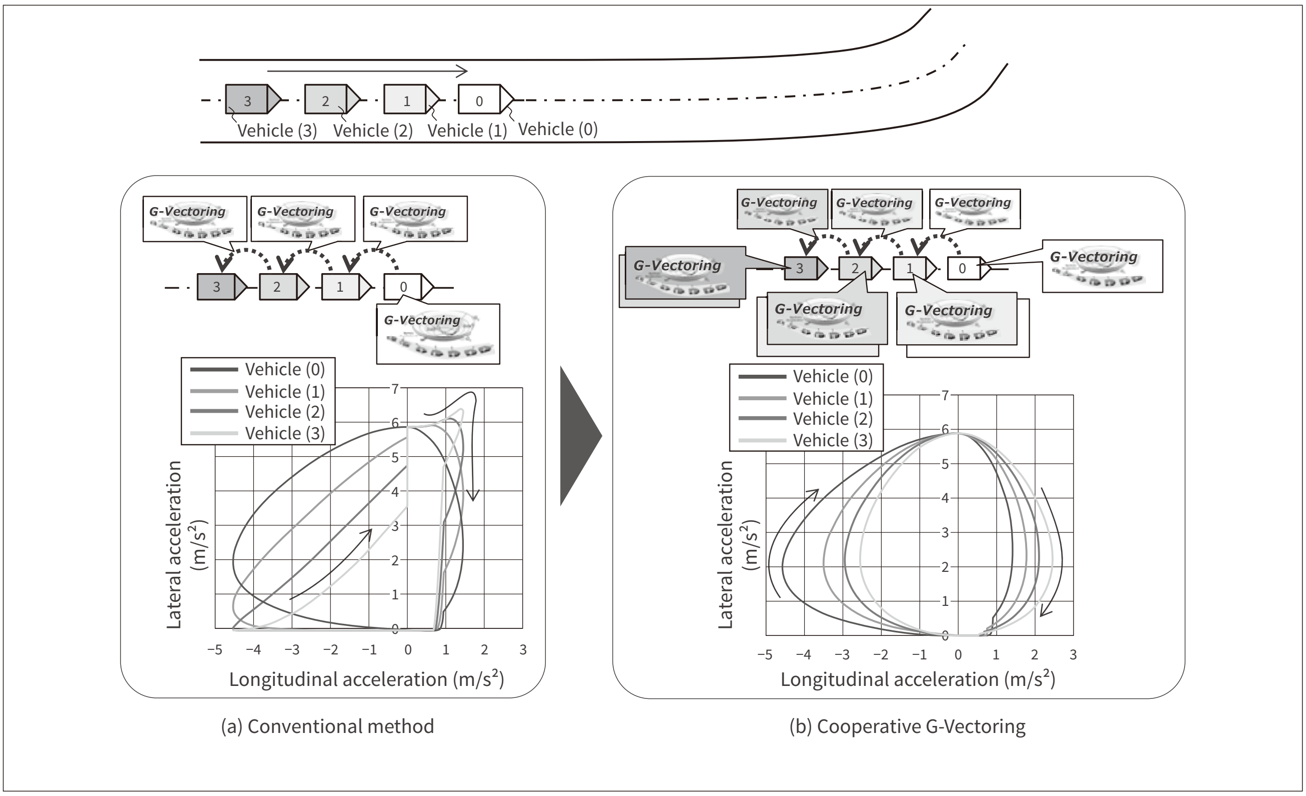
Systems for driverless platooning, whereby vehicles follow behind a lead vehicle and automatically maintain the correct speed and inter-vehicle distance, are seen as a means of reducing labor requirements in road freight. Highway trials have been conducted under the guidance of the Ministry of Land, Infrastructure, Transport and Tourism and the Ministry of Economy, Trade and Industry as part of the "Research and Development/Demonstration Project for Implementation of an Advanced Autonomous Driving System in Society"[(1)]. Platooning is also potentially useful for smaller vehicles used for personal travel or freight on city or other non-highway roads, providing flexible mobility that can be tailored to user needs such as destination and purpose of travel while also allowing for efficiency.

As such urban and non-highway roads feature a wider range of cornering conditions than highways, the control of acceleration and deceleration when cornering has a significant effect on passenger comfort as well as on things like travel time and safety. Accordingly, Hitachi has devised a technique for ensuring that changes in acceleration and deceleration during cornering are appropriate. An adaptation for platooning of the G-Vectoring technique[(2)] that Hitachi derived from the driving practices of expert drivers, the technique, called Cooperative G-Vectoring[(3)], can provide platooning vehicles with safe, comfortable, and efficient control of cornering.

G-Vectoring combines safety and efficiency by controlling acceleration and deceleration during the transition periods of variable lateral acceleration as the vehicle enters or exits a corner, coordinating acceleration and cornering to ensure that the changes in acceleration feel smooth to passengers[(2)]. Unfortunately, if this technique is combined with conventional platooning control without modification, it will control the following vehicles based on the timing and amount of acceleration and deceleration used by the lead vehicle. This is problematic because each vehicle enters the corner at a different time and therefore following vehicles will experience inappropriate changes in acceleration [see **Figure 2** (a)]. Furthermore, if G-Vectoring control is implemented independently on each vehicle in a platoon, differences in deceleration timing at corner entry can shorten up the inter-vehicle distances. This makes it difficult to use the short gaps between vehicles that improve the efficiency of platooning. In response, Hitachi has used simulations to demonstrate that it is possible to ensure that changes in acceleration are smooth for all vehicles in the platoon

Figure 2 — Benefits of Using Cooperative G-Vectoring for Cornering by Platooning Vehicles

Using a graph that plots the longitudinal acceleration due to vehicle acceleration and deceleration against the lateral acceleration due to cornering to express the changes in acceleration experienced by platooning vehicles as they enter a corner shows how, when using the conventional method (a), the following vehicles (2) and (3) do not experience the smooth arc-shaped change in acceleration that is best for passengers. This occurs because control of the following vehicles is based on the acceleration and deceleration of the lead vehicle. When using Cooperative G-Vectoring (b), in contrast, the change in acceleration traces a smooth arc-shaped pattern for all of the vehicles by first controlling how the following cars accelerate and decelerate around the corner based on information from the lead car.



without the inter-vehicle gaps becoming any shorter than the specified distance by sharing G-Vectoring control parameters among the vehicles and using accelerations and decelerations that are based on the G-Vectoring control quantities from the lead vehicle but start with the following vehicles first [see **Figure 2** (b)]. Hitachi hopes to use this technique for platooning on urban roads in the future, seeing it as a means of controlling driving in a way that considers passenger comfort without compromising safety.

2. 2 Traffic Flow Control at Intersections for Safe and Efficient Transportation

Preventing accidents and keeping traffic flowing smoothly through intersections are among the important challenges for autonomous driving. While the control of traffic flow through intersections has already been the subject of considerable research[(4)–(9)], most of this has required the use of high-performance computers to calculate the timing and speed at which each vehicle should enter the intersection. Given the need for due consideration of external factors such as transmission delays or slow response times, the complexity of the control logic and associated development costs also raise concerns about the practicality of deploying such practices on ubiquitous small intersections. In response, Hitachi has developed a traffic flow control technique that incorporates the idea of roundabouts, a form of intersection that has become more common in Japan over recent years, and the blockage system that has long been used on railways to only allow trains to use particular sections of track that they have been granted the right to use.

Specifically, this works by dividing an intersection into areas and by using electronic tokens (one token per area) exchanged between the supervisory control system and vehicles to grant exclusive access to each area. Treating the intersection like a roundabout, the vehicles request access to each area they need to drive through from the supervisory control system and only enter particular areas after they have first been granted access by way of an electronic token from the system.

The technique was implemented on a traffic flow simulator for the four-way intersection shown in **Figure 3** and the behavior of each vehicle determined under conditions of between 100 and 600 vehicles/h from each road. The results demonstrated that, despite only exchanging a very small amount of information between the supervisory control system and vehicles, smooth traffic control could be maintained with no more than one vehicle being in each area at

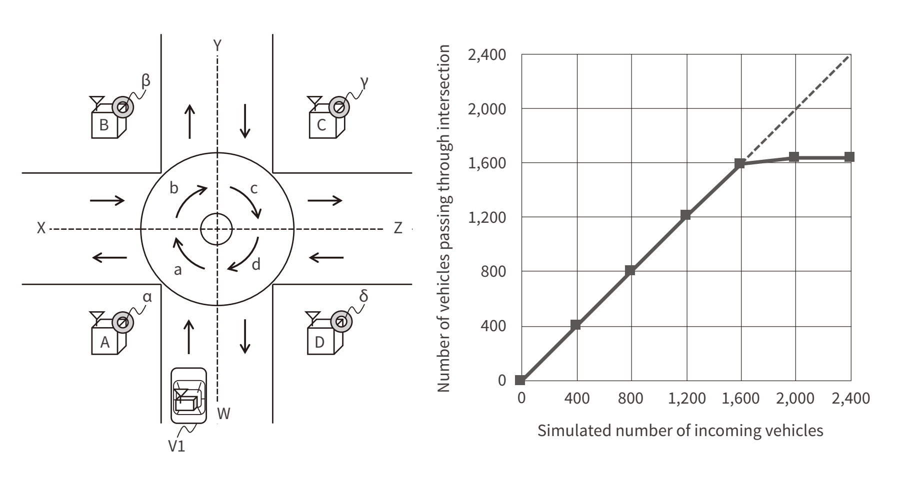


Figure 3 — Benefits of Using Electronic Tokens (α, β, γ, and δ) for Traffic Flow Control at Roundabout

The safe and smooth flow of traffic through the intersection is achieved by only allowing one vehicle into each area at a time and only having as many electronic tokens for this purpose as there are areas. The suitability of this technique for controlling the flow of traffic through a roundabout was demonstrated in a simulation where it kept traffic flowing without congestion at a level of 1,600 vehicles/h (400 vehicles/h from each feeder road).

any one time and with the number of vehicles allowed to enter the intersection being limited to no more than the number of areas.

The associated algorithm[(10)] has wider applications beyond intersections. One example would be its use to control the flow of merging traffic. In the future, Hitachi intends to use it to control the flow of traffic in a wide range of situations where autonomous vehicles cross paths.

2. 3 Graceful Degradation Design Technique for More Reliable Control of Autonomous Driving

When an autonomous driving system suffers from a hardware fault or when poor weather conditions prevent sensors or algorithms from performing as they should, the system should be able to continue driving safely long enough to reach a safe location. One way of achieving this is known as “graceful degradation,” an approach used in space and aerospace systems where autonomous capabilities are more advanced. The difficulty with implementing graceful degradation on autonomous driving systems in which different types of sensors are used to back up one another is the large amount of design work involved in considering the many ways in which performance degradation can occur across 10 or more sensors and then designing degradation functions for each case. To maintain safety, a guarantee is also needed that the system will be able to switch over to these degradation functions within the limited time available after something goes wrong. The problem with conventional techniques for assessing real-time performance, however, is that they deliver overly pessimistic results and so cannot provide accurate switchover times because they work by summing the worst-case execution times for each operation without distinguishing between different system conditions.

To solve this problem, Hitachi has come up with graceful degradation design and testing techniques that enable degradation to occur progressively depending on what is causing the loss of performance. Their suitability has been demonstrated on a prototype[(11)] (see **Figure 4**). This new method involves first performing separate degradation design for each level of restricted performance corresponding to different situations in which hardware faults or driving conditions prevent full performance, and then analyzing situations in which more than one problem happens at the same time. Doing it this way reduces the amount of design work needed to implement highly reliable autonomous driving systems by enabling the re-use of degradation designs in situations where the same control functions remain available despite the loss of performance having different causes. By assessing real-time performance on the basis of worst-case times for detection, decision-making, and degradation control and the control responses specified in the degradation design for each type of performance loss, it is possible to limit the evaluation of switchover times to only those degradation patterns that could potentially occur in practice.

When this method was used on a prototype level-three autonomous driving system with more than 10 sensors, it found that autonomous driving should be able to remain in operation under 86.1% of the different types of performance loss. Likewise, an assessment of real-time performance found a 35.3% performance improvement over the conventional technique. Hitachi intends to use the new method in the degradation design and validation of autonomous driving systems.

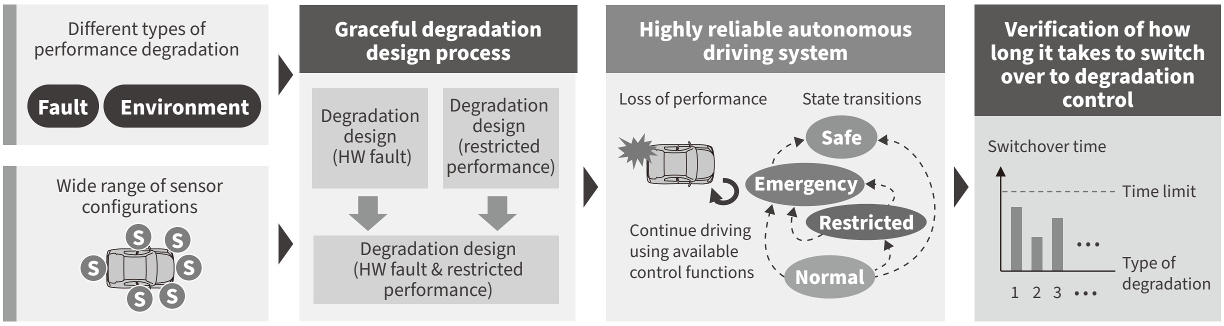
3. Conclusions

As cars come to play a very different role in society and amid proposals for a wide variety of mobility services based on autonomous driving, putting these proposed services into practice will require a diverse range of technologies to underpin their safety, comfort, and economics.

This article has described a number of newly developed techniques intended to achieve this. Along with these

Figure 4 — Graceful Degradation Design and Verification Technique that Enables Progressive Downgrading of Autonomous Driving System

The technique enables efficient degradation design by analyzing different levels of potential performance degradation on autonomous driving systems with a wide range of sensor configurations. Similarly, use of state transition information in the verification of how long it takes to switch over to degradation control provides a highly accurate assessment of whether the switchover for each state transition can be done in the time available.



HW: hardware

techniques, Hitachi is also contributing in other ways to the practical realization of mobility systems that support the mobility and transportation of people. In applications from driving support to autonomous driving, these include the extensive deployment of technologies ranging from onboard vehicle sensing to driving control and secure interoperation with other infrastructure systems.

References

1) Ministry of Economy, Trade and Industry News Release, “Embarking on Demonstration Tests of Autonomous Driving System using Driverless Trucks in Caravan to Travel on Public Expressways” (Jan. 2019) in Japanese, http://www.meti.go.jp/press/2018/01/20190108001/20190108001.html
2) M. Yamakado et al., “Improvement in Vehicle Agility and Stability by G-Vectoring Control,” Vehicle System Dynamics, Vol.48, pp. 231–254 (Dec. 2010).
3) J. Takahashi, et al., “Study of Longitudinal-Acceleration Control Based on G-Vectoring for Vehicle-Platooning,” Transactions of Society of Automotive Engineers of Japan, Vol. 50, No. 5, pp. 1383–1389 (Sept. 2019) in Japanese.
4) Volvo Car Corporation, “Volvo Car Corporation tackles changes in driving behaviour with new safety systems,” https://www.media.volvocars.com/global/en-gb/media/pressreleases/44364
5) K. Dresner, et al., “A Multiagent Approach to Autonomous Intersection Management,” Journal of Artificial Intelligence Research, vol. 31, pp. 591–656 (Mar. 2008).
6) T. Ogitsu, et al., “Automatic Driving Control for Passing through Intersection by use of Intersection Traffic Management System,” Transactions of Society of Automotive Engineers of Japan, Vol. 41, No. 6, pp. 1273–1278 (Nov. 2010) in Japanese.
7) J. Lee, et al., “Development and Evaluation of a Cooperative Vehicle Intersection Control Algorithm Under the Connected Vehicles Environment,” IEEE Transactions on Intelligent Transportation Systems, Vol. 13, Iss. 1, pp. 81–90 (Mar. 2012).
8) W. Wu et al., “Distributed Mutual Exclusion Algorithms for Intersection Traffic Control,” IEEE Transactions on Parallel and Distributed Systems, Vol. 26, Iss. 1, pp. 65–74 (Jan. 2015).
9) S. Okada, et al., “Study on Cooperative Driving of Automated Driving Vehicles through Shared Spatial Information Infrastructure,” Transactions of Society of Automotive Engineers of Japan, Vol. 47, No. 5, pp. 1197–1204 (Sept. 2016) in Japanese.
10) K. Katsuta, et al., “Traffic Flow Control Method at Intersection by Electronic Token,” Transactions of Society of Automotive Engineers of Japan, Vol. 51, No. 5, pp. 836–841 (Sept. 2020) in Japanese.
11) T. Ishigooka, et al., “Graceful Degradation Design Process for Autonomous Driving System,” 38th International Conference on Computer Safety, Reliability and Security (SAFECOMP), pp. 19–34 (Aug. 2019).

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