Cooperative Driving of Automated Vehicles with Inter-vehicle Communications

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Abstract
This paper deals with cooperative driving of automated vehicles on highways with data transmission based on inter-vehicle communications. It presents a data transmission algorithm in a platoon for a unidirectional medium and an omni-directional one under both a steady state and a transient state. The algorithm is featured by that the throughput rate is larger than a conventional system, when the number of vehicles in a platoon is less than 15. This paper also focuses on merging, which is the typical case of cooperative driving, and presents a merging control algorithm that makes the best use of the inter-vehicle communications. The results of a simulation study and an indoor experiment show the feasibility of the algorithms of the data transmission and merging control.

1 Introduction
Communications in the Intelligent Transportation Systems (ITS) include wide area wireline communications, wireless communications, short-range wireless communications, and vehicle-to-vehicle communications [1]. This paper deals with the vehicle-to-vehicle communications or the inter-vehicle communications applied to AVCSS (Advanced Vehicle Control and Safety Systems). AVCSS will play an important role in ITS, because AVCSS could provide essential solutions to the issues of accidents, congestion, pollution, and energy consumption in road traffic.

The inter-vehicle communications are one of the key technologies in AVCSS. Road-vehicle communications, which are one of the key technologies in ATMS/ATIS (Advanced Traffic Management Systems / Advanced Traveler Information Systems), have been applied to route guidance systems and electronic toll collection systems, the services of which have already started. On the other hand, the inter-vehicle communications are still at the phase of research, and only the experiments of the inter-vehicle communications applied in the automated highway systems have been conducted [2, 3].

This paper deals with data transmission through inter-vehicle communications for vehicle control, and presents algorithms of the data transmission and merging control of a vehicle into a platoon on a highway, as a case of cooperative driving.

2 Data transmission
2.1 Data transmission algorithm
Under platooning and cooperative driving, data transmission among vehicles is essential to the lateral and longitudinal vehicle control. Since the number of vehicles is not usually large, it is possible to employ a pure ALOHA (additive links online Hawaii area) system. There are, however, more effective systems than the ALOHA system, and they are a TDM (time division multiplexing) system or a round robin system, which are featured by a fast transmission rate necessary for vehicle control as well as collision avoidance capability. The TDM system requires that the number of slots, each of which is assigned to each vehicle in a platoon, be fixed in advance and, therefore, it is not flexible in some applications.

This paper presents a data transmission algorithm, which is based on a round robin system. The algorithm is flexible enough to change the transmitting path dynamically when a new vehicle joins the platoon or a vehicle in a platoon leaves. It will be explained when an omni-directional medium is employed, followed by when a unidirectional one is employed.

2.2 Algorithm description
2.2.1 Algorithm under steady state
When an omni-directional medium including the microwave is employed in a platoon under a steady state, the data are transmitted from a vehicle to another at a time. It is assumed that each vehicle knows its
own identification number (ID) in the platoon and the number of vehicles, \( n \), in the platoon. The ID means the sequence of the transmission, and it does not depend on the physical position of a vehicle in the platoon. At time \( j \), the \( i \)th vehicle transmits data to the \((i + 1)\)th vehicle, and the data are also received by the \((i - 1)\)th as the acknowledgment of the transmission. At time \((j + 1)\), the \((i + 1)\)th vehicle transmits data received from the \(i\)th vehicle and modified in the \((i + 1)\)th to the \((i + 2)\)th as well as to the \(i\)th. The \(n\)th vehicle transmits to the 1st vehicle, which will indicate the conclusion of one transmission cycle. The network of the inter-vehicle communications makes a ring. The slots do not necessarily have the same length.

### 2.2.2 Algorithm on vehicle joining

If a new vehicle, the \((n + 1)\)th vehicle, tries to join the ring and transmits the request, communication collision will occur. Provision of interrupt detective gaps between slots assigned to each vehicle as shown in Figure 2 would prevent the collision and give the \((n + 1)\)th vehicle a chance to join the ring. During the interrupt detective gaps, all the vehicles are in the receiving mode, and the \((n + 1)\)th vehicle can transmit the request to each vehicle that has just finished the transmission or is about to start the transmission. Then, a new sequence will start among the \((n + 1)\) vehicles. When a vehicle tries to leave a platoon, it will transmit the declaration. After all the vehicles recognize the declaration, the vehicle can leave, and the new sequence of the data transmission will start.

![Figure 2: A mechanism to join a new vehicle into a platoon](image)

### 2.2.3 Transmission with a unidirectional medium

When a unidirectional medium including laser and millimeter wave is employed, the sequence of the data transmission depends on the physical locations of vehicles in a platoon. The ID of each vehicle indicates its physical location in a platoon, and the data, thus, are transmitted from a vehicle to the following. Almost all the sequence of the data transmission in this case is the same to the case when an omni-directional medium is employed, but there are two differences; one is the transmission of the acknowledgment, and the other is a procedure when a new vehicle tries to join the platoon. When a unidirectional medium is employed, the transmission of the conclusion of one cycle has to be relayed back from the \(n\)th vehicle to the 1st vehicle. This will need additional time when compared to the transmission with an omni-directional medium. When a new vehicle, the \((n + 1)\)th vehicle, joins the platoon, it must be behind the \(n\)th vehicle. After the \(n\)th vehicle transmits data to the back as well as to the \((n - 1)\)th vehicle, if the \(n\)th vehicle receives a response from the back, it can recognize there is the \((n + 1)\)th vehicle, and a new network in a platoon consisting of \((n + 1)\) vehicles starts.

### 2.3 Performance evaluation

The performances of the data transmission algorithms proposed here and of the TDM system [2] have been numerically evaluated. In the evaluation, it is assumed that the packet length is 128 bytes; the length of the guard bits between packets is 32 bits; the transmission rate is 1.54 Mbps; the length of the interrupt detection gap is one tenth of the transmission time of one packet. Figure 3 shows the evaluation in a relative measure. In the TDM system, the slots for the data transmission are provided in advance, and the number of that is 30 in the system cited here [2]. The throughput rate of the TDM system is, thus, constant to a maximum of 30 vehicles. The evaluation shows that the throughput rate of the round robin system with an omni-directional medium is several times as large as that of the TDM system, when the number of the vehicles is within 10, which is the ordinary number of vehicles in a platoon.

![Figure 4: A maximum time required for a new vehicle to join an inter-vehicle communication network established in a platoon](image)

Figure 3 shows a maximum time required for a new vehicle to join an inter-vehicle communication network established in a platoon. In the TDM system, the time becomes longer as the number of vehicles in a platoon increases, because the chance to find an unassigned slot becomes less. In the algorithm proposed here, if the number of vehicles in a platoon increases, more
Figure 3: Comparison of maximum throughput rates

Figure 4: Comparison of time required to join a new vehicle into a communication network

time is required to send the acknowledgment to the 1st vehicle, but the time in the round robin system is much less than in the TDM system.

### 2.4 Two-layer structure for inter-vehicle communication

The data transmission algorithm proposed here will be discussed in terms of the layer of the communications. The data transmission algorithm presented here uses one communication layer. If the algorithm is applied to inter-platoon communications, the protocol will be complex. In order to avoid the complexity, the use of two communication layers, the intra-platoon communications and the inter-platoon communications have been proposed [4] (Figure 5).

When the two-layer structure is employed, the transient of the network including joining and leaving can be simplified.

Figure 6 (a) shows a case that a ring-network B joins into the main ring-network A. Figure 6 (a)-(1) is the state before restructuring. At first, the lead vehicle 1 of the main ring-network A inserts the command that changes the transmitting path from the last vehicle 4 of the ring-network A to the lead vehicle 11 of the ring-network B into the data of the intra-platoon communications and transmits new data to vehicle 2. The last vehicle 4 of the ring-network A receives the data and then changes the transmitting path from the lead vehicle 1 to another lead vehicle 11 of the ring-network B (Figure 6 (a)-(2)). The vehicle 4 inserts the command that changes the transmitting path from the lead vehicle 11 of the ring-network B to the lead vehicle 1 of the ring-network A into the transmission data and transmits new data to the vehicle 11. The last vehicle 13 of the ring-network B receives the data and then changes the transmitting path from the vehicle 11 to the lead vehicle 1 of the ring-network A (Figure 6 (a)-(3)). Restructuring of a ring-network is finished.

Figure 6 (b) shows a case that a ring-network A separates two ring-networks. The leaving vehicle 2 of the main ring-network A inserts the command that changes the transmitting path from the own vehicle 2 to the vehicle 4 into the data of the intra-platoon communications and transmits new data to the vehicle 3. The vehicle 3 receives the data and then changes the transmitting path from vehicle 4 to the new lead vehicle 2 of the new ring-network B (Figure 6 (b)-(2)). Restructuring of a ring-network is finished.

Figure 6 (b) shows a case that a ring-network B separates two ring-networks. The leaving vehicle 2 of the main ring-network B transmits the received command to vehicle 4 using the old path, and, at the same time, transmits new data to the lead vehicle 2 of the ring-network B using a new path. The lead vehicle 1 of the ring-network A receives the data and then changes the transmitting path from the vehicle 2 to the vehicle 4 (Figure 6 (b)-(3)). Restructuring of a ring-network is finished.

The procedure of the data transmission algorithm is described in the style of the Pascal language. First,
the inter-platoon communications is as follows:

**procedure** InterCommunication ()
**begin**
  **loop**
  The lead vehicle transmits the ID number, the position, and etc. to other lead vehicles broadcasting every $t$ times.
  If the lead vehicle wants to join into another ring-network, it transmits a message of a request of joining (Figure 5).
  When the lead vehicle receives a message,
    case 1:
      If the message is a request of joining, the lead vehicle transmits a message of permission of joining (Figure 5).
    case 2:
      If the message is permission of joining, the lead vehicle commands joining against the own ring-network.
  **end**
**end**

Next, the intra-platoon communications is as follows:

**procedure** IntraCommunication ()
**begin**
  **loop**
  If a vehicle receives a message during an interruption detective gap, it makes the process of interruption (Figure 2).
  When the vehicle receives a message,
    case 1:
      If the lead vehicle receives the message of the command of joining, it transmits the command of sorting to other vehicles.
    case 2:
      If a vehicle (except the lead one) receives the message of the command of joining, it makes the process of joining (Figure 6 (a)).
    case 3:
      If the message is the command of leaving, it makes the process of leaving (Figure 6 (b)).
    case 4:
      If the message is the command of sorting, it makes the process of sorting.
  **end**
  The $i^{th}$ vehicle transmits the ark to the $(i - 1)^{th}$ one, transmits the message, the position, and etc. to the $(i + 1)$ one, and receives the ark from the $(i + 1)^{th}$ one (Figure 1).
**end**

**3 Vehicle merging control**

The merging control algorithm provides a way to merge a vehicle into through traffic at a ramp or into a platoon on lane changing on highways as safely and efficiently as possible. For simplicity, it is assumed that all vehicles are driving at the same speed, and have the same dynamics. The merging of a platoon into another platoon is regarded as the same as merging of a single vehicle into a platoon, since the merging of the platoon can be resolved into a series merging of a single vehicle.

**3.1 Merging control algorithm**

The merging control algorithm used here employs a concept of a virtual vehicle that is generated by mapping a vehicle on a lane onto an object lane in order to longitudinally control a vehicle on the object lane with the virtual vehicle (Figure 7). The detail of the virtual vehicle and the merging control algorithm has been shown in [4].

The data transmission algorithm on the merging is based on the algorithm when a new vehicle joins a platoon. The use of an omni-directional medium is preferable, but a unidirectional medium can also be employed, if the data are transmitted over inter-vehicle communications via road-vehicle communications, or vehicle-road-vehicle communications.

**3.2 Simulation study**

A simulation study has been conducted to show the feasibility of the merging control algorithm. It is assumed that two platoons, each of which consists of five vehicles, are on a sub lane (a ramp) and on a main lane, as shown at the top of Figure 8. The parameters in the simulation are: the initial speed of the vehicles is 22.2 m/sec; the range of the acceleration and deceleration of the vehicles is within 0.1 G; the set headway is 20 m; the control period is 10 msec; the communication range is 300 m; and the communication cycle is 10 msec. The result of the simulation is shown at the bottom of Figure 8. One platoon alternately merges into the other platoon. A longitudinal
control algorithm [5] is used for the vehicle control on the merging.

4 Experiment with small vehicles

An indoor experiment has been conducted with three small indoor vehicles to verify the feasibility of the algorithm. The algorithms of the data transmission and the merging control have been implemented in the vehicles. The inter-vehicle communications employ a wireless LAN, the carrier frequency is 2.4 GHz, and the bit rate is 1.6 Mbps. Since the data transmission algorithm is implemented with the wireless LAN protocol, some characteristics including the transmission error and the retry on errors cannot be implemented. The three vehicles are identical, and of two wheel differential type. The maximum speed of the vehicles is 0.1 m/sec. The agenda of the experiment is merging on lane changing. In the initial conditions, two of the vehicles are on a main lane with the headway of 0.8 m, and the third one is on the next lane, which is supposed to cut into the two vehicles on the main lane. The width of the lanes is 0.9 m, and the third vehicle, thus, moves laterally for 0.9 m. The merging is supposed to be finished till the vehicle drives for 2 m.

The data which each vehicle transmits in the communications is in a frame of fixed length of 256 bytes, and consist of the identification number of the vehicle, the position \((x, y)\), the heading, the headway and the deviation from the preceding vehicle, the acceleration, the speed, the status of the vehicle including free agent driving or following, the distance to the merging point, the existence of the preceding vehicle, and the existence of the vehicle which cuts in.

Figure 10 shows an experiment of the merging. The longitudinal control algorithm [5] and the lateral control algorithm [6] have been employed in the experiment. At the initial state, the ring-network is formed within the platoon of the vehicle 1 and 2 on the main lane. When the vehicle 1 recognizes the existence of the vehicle 3, the vehicle 1 begins to communicate with the vehicle 3 through the inter-platoon communications, and then the ring-network of the three vehicles is formed. When the vehicle 3 recognizes that it has to merge between the vehicles 1 and 2, the vehicle 3 generates a virtual vehicle 1' ahead, and the vehicle 2 begins to decrease the speed in order to double the headway between the vehicles 1 and 2 by the time when the vehicle 3 reaches the merging point. In Figure 10 (a), the vehicle 3 begins the preparation of the merging at 12 sec after the start, and the vehicle 2 also begins at 16 sec after the start. The longitudinal control decreases the speed of the vehicle 3 to make the headway from 0.8 m to 1.6 m for the cutting.

5 Conclusions

The inter-vehicle communications have been described with focusing on its application to the merging control of vehicles at a ramp or on lane changing on highways. Although the feasibility of the algorithms for the data transmission and for the merging control has been shown with the simulation studies and the indoor experiment with small vehicles, the algorithms should be improved when they are implemented in vehicles in the real world. There are many problems to be solved in the inter-vehicle communications including the media and the protocol for practical use.
- Velocities of the vehicles (inputs to motors)
- Distances between the vehicles (estimated with the motor inputs)
- Trajectories of the vehicles (estimated with the motor inputs)

(a) Velocities of the vehicles (inputs to motors)  (b) Distances between the vehicles (estimated with the motor inputs)

(c) Trajectories of the vehicles (estimated with the motor inputs)

(d) A series of scenes of merging

Figure 10: Experimental results of merging

References