Coordinated Control and Communication for Enhanced Safety of Highway Vehicle Platoons

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***Abstract*—Platoon formation has been identified as a promising framework in developing intelligent transportation systems. By autonomous or semi-autonomous vehicle control and inter-vehicle coordination, an appropriately managed platoon can potentially offer enhanced safety, improved highway utility, increased fuel economy, and reduced emission. This paper is focused on quantitative characterization of impact of communication systems on platoon safety. By comparing different information structures and contents, we reveal some intrinsic relationships between control and communications. The findings of this paper provide useful guidelines in sensor selection, communication resource allocation, and vehicle coordination in highway platoon control problems.**

I. Introduction

Controllers at vehicle levels, sensors and communication systems that permit information exchange, and coordination of the platoon at higher levels interact intimately in vehicle platoon formation and control. This paper investigate several key issues rising in such problems.

Platoon formation has been identified as a promising framework in developing intelligent transportation systems. By autonomous or semi-autonomous vehicle control and inter-vehicle coordination, an appropriately managed platoon can potential offer enhanced safety, improved highway utility, increased fuel economy, and reduced emission. In a platoon formation and maintenance, high-level distributed supervisors that reside in vehicles adjust vehicle spatial distributions based on inter-vehicle information via sensors and wireless communication networks such that roadway utilization is maximized while the risk of collision is minimized or avoided. Platoon control has drawn substantial attention lately, in the contexts of intelligent highway control and automated highway systems, with many methodologies and demonstration systems [1], [2]. Typical control functions include PID controllers, state feedback, adaptive control, state observers, among others, with safety, string stability, and team coordination as the most common objectives [3], [4], [5]. In our recent paper [6], a weighted and constrained consensus control method was introduced to achieve platoon formation and robustness against disturbances, vehicle addition and departure, and communication channel uncertainties. At present, on-board sensors are used in vehicle distance measurements. [6] employs convergence rates as a performance measure to evaluate additional benefits of different communication topologies in improving platoon formation, robustness, and safety.

In general, communication channels insert new dynamic subsystems into control loops. As such they play essential roles in control design. Recent pursuit on interaction between communication systems and feedback loops treats communication systems as added uncertainty such as delays and errors, or constraints such as quantization [7], [8], [9], [10], [11]. Coordinated design of communication channels and control systems remains mostly open.

In terms of coordination of control and communication systems, especially in automotive applications, some intrinsic questions concerning quantitative impact analysis of communication systems on safety in platoon control remain largely unanswered: (1) How much improvement of safety can be achieved by a communication channel? (2) How will communication uncertainties such as delays, packet loss, and errors affect safety?

This paper aims to answer these questions with quantitative characterization. To facilitate this exploration, we start with a basic platoon of three vehicles. Various information structures are considered: (1) Sensors only; (2) Combined sensor and wireless communications. In addition, we investigate the information contents: (1) Distances only; (2) Distance and speed. The findings of this paper will be useful to guide design of information infrastructures, information contents, control strategies, and resource allocation in platoon control problems.

II. Problem Formulation

A. Systems

This paper is concerned with coordination of vehicles in a highway platoon. Vehicle dynamics will play important roles in this pursuit. For clarity of investigation, we will use simplified, generic, but representative vehicle dynamic models [15]

$$m\dot{v} + f(v) = F \tag{1}$$

where m (Kg) is the consolidated vehicle mass (including the vehicle, passengers, etc.), v is the vehicle speed (m/s), $f(v)$ is a nonlinear function of v representing resistance force from aerodynamic drag and tire/road rolling frictions, and F (Newton or Kg-m/s^2) is the net driving force (if $F > 0$) or braking force (if $F < 0$) on the vehicle's gravitational center. Typically, $f(v)$ takes a generic form $f(v) = a + bv^2$, where the coefficient $a > 0$ is the tire/road rolling resistance and $b > 0$ is the aerodynamic drag coefficient. These parameters depend on many factors such as the vehicle weight, exterior profile, tire types and aging, road conditions, wind strength and directions. Consequently, they are usually determined experimentally and approximately. This paper is focused on longitude vehicle movements within a straight-line lane. Consequently, the vehicle movement is simplified into a one dimensional system.

Vehicles receive neighborhood information by using sensors and communication systems. We assume that radar sensors are either installed at front or rear of the vehicle. The raw data from the sensors are distance information between two vehicles. Although it is theoretically possible to derive speed information by signal processing (derivatives of the distances), this paper works with the direct information and leaves signal processing as part of control design. As a result, sensor information will be limited to distances. In contrast, a communication channel from vehicle i to vehicle j can transmit any information that vehicle i possesses. We will consider the following information contents: (1) Vehicle i's distance to its front vehicle, which is available by its own front sensor; (2) Vehicle i's speed, which is available by its own speedometer; (3) Vehicle i's pedal action, such as acceleration and braking. Information structures are depicted in Fig. 1. A vehicle may receive information from its front sensor (on its distance to the front vehicle), or its rear sensor (on its distance to the vehicle behind it), or wireless communication channels between two vehicles. The wireless communication channels may carry different information contents, such as distance, speed, driver's action, etc., which is available at the sending vehicle.

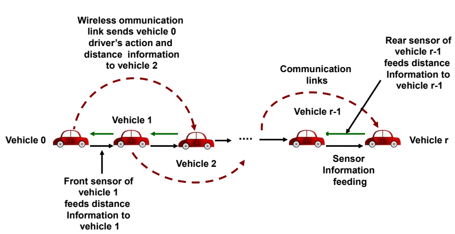

Fig. 1. Information structures

For concreteness, we will use a basic three-car platoon to present our key results. Although this is a highly simplified platoon, the main issues are revealed clearly in this system. Three information structures are studied, shown in Fig. 2. Information Structure (a) employs only front sensors, implying that vehicle 1 follows vehicle 0 by measuring its front distance d_1, and then vehicle 2 follows vehicle 1 by measuring its front distance d_2. For safety consideration, this structure provides a benchmark for comparison with other information structures. Information Structure (b) provides both front and rear distances. Then Information Structure (c) expands with wireless communication networks.

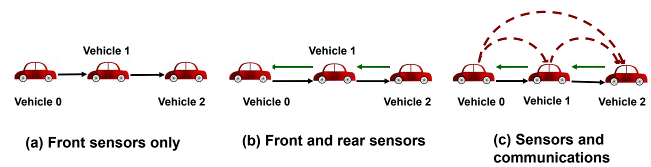

Fig. 2. Three main information structures: (a) Only front distance information is available for vehicle control. (b) Both front and rear distances are available. (c) Additional information is transmitted between vehicles.

The platoon in Fig. 2 has the following local dynamics.

$$\left\{\begin{array}{lcl} \dot{v}_0 &=& \frac{1}{m_0}(F_0 - (a_0 v_0 + b_0 v_0^2)) \\ \dot{v}_1 &=& \frac{1}{m_1}(F_1 - (a_1 v_1 + b_1 v_1^2)) \\ \dot{v}_2 &=& \frac{1}{m_2}(F_2 - (a_2 v_2 + b_2 v_2^2)) \\ \dot{d}_1 &=& v_0 - v_1 \\ \dot{d}_2 &=& v_1 - v_2 \end{array}\right. \qquad (2)$$

where F_0 is the leading vehicle's driving action and viewed as an external disturbance, and F_1 and F_2 are local control variables.

B. Feedback Control

For safety consideration, the inter-vehicle distances d_1 and d_2 have a minimum distance $d_{min} > 0$. To ensure that the vehicles 1 and 2 have sufficient distance to stop when the leading vehicle 0 brakes, a normal distance d_{ref} is imposed. Apparently, the larger d_{ref}, the safer the platoon, under any fixed control strategies. However, larger d_{ref} implies more consumption of the highway space resource. As a result, it is desirable to use as small d_{ref} as possible without compromising the safety constraint.

There are numerous control laws which have been proposed or commercially implemented [12], [13]. Since the focus of this paper is on impact of information structures and contents rather than control laws, we will impose certain simple and fixed control laws. For safety consideration, we concentrate on the case when the distance is below the nominal value $d < d_{ref}$. The control law involves a normal braking region of a linear function and an enhanced braking region of a sharp nonlinear function towards the maximum braking force . We will denote this function as $F = g_1(d)$.

Similarly, if vehicle i's speed information is transmitted to another vehicle j, the receiving vehicle can use this information to control its braking torque. This happens when $v_j > v_i$. The larger the difference, the stronger the braking force. This control strategy may be represented by a function $F = g_2(v_j - v_i)$.

C. Communication Latency

Inter-vehicle communications use wireless networks which are subject to far severe uncertainties than wired networks (such as CAT5e/CAT6) and introduce many uncertain and random elements into the networked control system. For example, one critical measure of signal strength is the signal-to-interference-plus-noise ratio (SINR). The SINR attenuates with distance (it decreases inverse proportionally to the cubic of the distance between the two vehicles). It is also affected critically by obstructions, such as buildings, bridges, trees, houses, other vehicles, etc. Other essential factors include queue delays, network data traffic conditions, routes, signal fading caused by multi-path transmission of the signals and their interactions, signal interference from other vehicles, Doppler shifts, traffic and weather conditions. These uncertainties vary significantly in different communication networks, such as broadcasting, dedicated Ad Hoc networks, etc. In addition, channel coding schemes and transmission protocols influence channel reliability significantly.

These factors collectively determine packet delivery delays, packet loss rates, etc. which are seen by the end user. This paper will focus on delay effects. Other communication uncertainties will be teated in separate papers. To be concrete in treating communication systems, we will employ IEEE 802.11 standards as our benchmark systems and the related latency data [14].

III. Communication System Case Studies

A. Basic Data Transmission Schemes

To study more realistically how communication systems and control interact, we will use the communication scheme that each data packet is generated at the sending site. The packet joints the queue for channel occupation and transmission. The queuing time depends on network traffic and data priorities, and hence is a random process. The packet contains both data bits and error checking bits. We assume that the embedded error checking mechanism is sufficient to detect any faulty packet. If the packet transmission is successful, the receive returns to the sender an acknowledgment message, which completes the packet transmission. On the other hand, if the packet is received with error, it will be discarded. Then a re-transmission request is sent back to the sender to re-transmit the same packet.

Inter-vehicle communications (IVC) can be realized by using infrared, radio, or microwaves waves. At present, microwaves have been identified as favored choice for inter-vehicle communications. For instance, in IEEE 802.11p, a bandwidth 75 MHz is allotted in the 5.9 GHz band for dedicated short range communication (DSRC) [14]. Alternatively, ultra-wideband (UWB) technologies also have been used for IVC. Historically, there are several wireless standards that have been studied inter-vehicle use, especially IEEE 802.11x, where $x \in \{a, b, g, p \dots\}$. Recently, many applications have been based on the DSRC with IEEE 802.11p at PHY and MAC layers. IEEE 802.11p is a modified version of IEEE 802.11 (WIFI) standard. IEEE 802.11g and IEEE 802.11p are used for experimental studies in this paper.

In the middle of protocol stack, DSRC employs IEEE 1609.4 for Channel Switching, 1609.3 for Network Service, and 1609.2 for Security Services. In the Network Service, users have a choice between Wireless Access for Vehicle Environments Short Message Protocol (WSMP) or Internet Protocol Version 6 (IPv6)+User Datagram Protocol (UDP)/Transmission Control Protocol(TCP). Single-hop messages typically use the bandwidth-efficient WSMP, while multi-hop packets use IPv6+UPD/TCP for its routing capability. We will discuss further details for these two protocols in the next two subsections.

B. A Single-Hop Experimental Study

We assume the three-vehicle case in Fig. 2. We emphasize that although we employ a three-car platoon for simplicity, it forms a generic base for study platoon safety issues. Here the vehicles in between the lead vehicle of the vehicle of interest are grouped as one pack, leading to the generic structure of Fig. 2.

Communication channels between v_0 and v_2 use the WSMP protocol. This protocol can carry messages on both the Control Channel (CCH) and the Service Channel (SCH). The WSMP allows the applications to directly control the lower-layer parameters such as transmission power, data rates, channel numbers and receiver MAC addresses. The WSMP over the CCH can skip the steps of forming a WAVE Basic Service Set (BSS) that delivers IP and WAVE short message (WSM) data on the SCH. Those methods can potentially reduce communication latency.

The round-trip time (RTT) under this protocol includes measurement time for the variables (vehicle distance, speed, etc.), source data creation time (creating packets, adding verification codes, scheduling, etc), communicating the packet to v_2, receiver verification, travel time for sending back acknowledgment from v_2.

In an ideal case that v_0 can capture the CCH during each CCH time slot, v_0 can send its beacon and update its status to v_2 at the rate of $10\ Hz$. If a package is successfully transmitted and verified during the first round, the RTT $\tau \leq 100$ ms since IEEE 1609.4 specifies the reoccurrence of the CCH at the rate of every 100 ms.

Example 1: A typical curve from [16] is re-generated here as shown in Fig. 3. When the modulation rate is 6 Mbps, the Package Delivery Rate(PDR) is about 0.75. If the first round trip takes 100 ms and each round trip catches the next CCH, it needs on average more than three retransmissions to achieve a PDR over 0.985, and hence the delay is more than 0.3 second. When the modulation rate is 18 Mbps,the PDR is 0.36. In order to meet the same required PDR, the delay time is more than 1 second.

C. Multi-Hop Communication Data

Inter-vehicle communications may involve multi-hops which create further delays. Typically, IPv6+UDP/TCP protocols can be used in such systems. Unlike the WSMP which

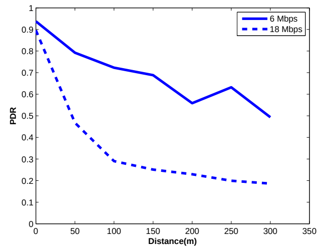

Fig. 3. PDR vs. separation distance under different data rates in the Rural Road(RR) environment (with 95% Confidence Interval). Here, data rate is 6 Mbps and 18 Mbps. Transmission power is 20 dBm.

uses 11 bytes overhead, IPv6 requires a minimum overhead of 52 bytes. Although this is more complicated in coding and less efficient in using the data resource, this protocol provides more flexible routing schemes. There are many experimental studies of IEEE 802.11p under multi-hop on highway environment. Since we are only concerned with latency data, we quote here the studies in [14] which contain extensive experimental results. A typical curve from [14] is re-generated in Fig. 4. It is noted that although IEEE 802.11p uses higher power and faster speed, a latency of hundreds of milliseconds is typical in highway conditions.

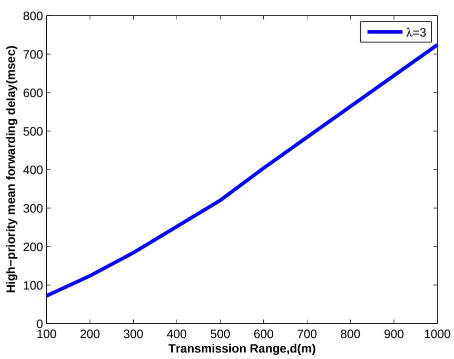

Fig. 4. Average delay of high-priority message dissemination for H = 5 hops of communication as functions of the transmission range

IV. Safety under Front Sensor Information

We start with the basic information structure of using front sensors only. For the three-car platoon in Fig. 2 and the control law $F = g_1(d)$ in (3), the closed-loop system becomes (2)

For simulation studies, we use some vehicle data from [15], with some parameter variations to represent a variety of vehicles. Under the MKS (metre, kilogram, second) system of units, the vehicle mass m has the range $1400 - 1800$ Kg, aerodynamic drag coefficient b has the range $0.35 - 0.6$ Kg/m. During braking, a (as the rolling resistance) is changed to tire/road slipping, which is translated into the braking force F (negative value in Newton). As a result, a is omitted.

Example 2: Three identical cars form a platoon. The vehicle mass $m = 1500$ Kg. The aerodynamic drag coefficients $b_0 = b_1 = b_2 = 0.43$. The nominal inter-vehicle distances are 40 m. The cruising vehicle speeds are 25 m/s (about 56 mph). The road condition is dry and the maximum braking resistance is 10000 N. This implies that when the maximum braking is applied (100% slip), the vehicle will come to a stop in 3.75 second. The braking resistance can be controlled by applying controllable forces on the brake pads.

The platoon uses only front sensors to measure inter-vehicle distances, namely the information structure (a) in Fig. 2. The feedback control function $F = g_1(d)$ is

$$\max\{k_1(d - dref) + k_2(d - dref)^3, -F_{max}\} \qquad (3)$$

where $d_{ref} = 40$ (m), $k_1 = 50$, $k_2 = 4$, $F_{max} = 10000$ (N). **Fast Braking Scenario:** Suppose that the leading vehicle uses a braking force 5000 N, which brings it to a stop from 25 m/s in 7.5 second. In this case, the minimum distances are 20.6 m for d_1 which is acceptable, but 0 m for d_2. This means that vehicle 2 will collide with vehicle 1 during the transient time.

To explain this scenario, we note that since vehicle 2 relies on d_2 to exercise its braking control function, there is a clear dynamic delay in initiating its braking although vehicle 0 started braking earlier. Due to fast braking, d_2 is reduced to about 20 m when vehicle 2 starts to act. It can be easily perceived that for a large platoon, this dynamic delay from vehicle to vehicle will be a severe safety concern.

V. Enhanced Information Structures and Contents

A. Adding Distance Information by Communications

Example 3: Continuing with Example 2, we consider the same three-car platoon under the same initial conditions: The nominal inter-vehicle distances are 40 m; the cruising vehicle speeds are 25 m/s (about 56 mph); the maximum braking resistance is 10000 N.

Under the **Fast Braking** scenario as in Example2, suppose now that vehicle 1 communicates with vehicle 2 by sending d_1 information to vehicle 2. As a result, vehicle 2 can now use both d_1 and d_2 in its control function.

Suppose that vehicle 2 modifies its braking control function from the previous $F_2 = g_1(d_2)$ to the new one $F_2 = 0.5g_1(d_2) + 0.5g_1(d_1)$. Now, the minimum distances are 20.6 m for d_1 and 15.9 m for d_2, both are within safety regions.

To compare Example 2 and Example 3, with information feeding of d_1 into vehicle 2, it is able to act earlier, resulting in a much reduced distance swing for d_2 during the transient.

B. Adding Speed Information by Communications

We now add the speed information of the leading vehicle to both vehicles 1 and 2 by communications.

Example 4: For the same three-car platoon under the same initial conditions as Example 3, we now add the leading vehicle's speed v_0 into the information structure. This information will be transmitted to both vehicles 1 and 2 by communications. Under the **Fast Braking** scenario as in Example 3, suppose now that vehicles 1 and 2 receive the additional speed information v_0, resulting in a new information structure.

From the control functions of Example 3, additional control actions $g_2(v_0, v_1)$ and $g_2(v_0, v_2)$ are inserted. Now, the minimum distances are 28.3 m for d_1 and 27.1 m for d_2, a much improved safety.

VI. Impact of Communication Delays

Example 5: Under the same system and operating condition as Example 3, we assume that the communication channel for the distance information has a delay of τ second. Without delay, the minimum distance for d_2 is 15.9 m. When a delay of $\tau = 0.6$ (second) is introduced, the minimum distance for d_2 is reduced to 11 m. Table I lists the relationship between the delay time and the minimum distance for d_2.

TABLE I
Impact of Communication Delays

delay time τ (s)	0	0.3	0.6	0.9	1.2
minimum d_2 (m)	15.9	13.6	11	8.2	5.1

Example 6: Under the same system and operating condition as Example 3, we first consider an ideal case. Assume that communication systems are using the single-hop scenario in Subsection III-B. Under a scenario of latency $\tau = 0.1$ second (CCH delay only), the minimum distance for d_2 is 15.1 m. It remains as an acceptable safe distance.

Example 7: Continuing the study of Example 6, we now consider the multi-hop scenario in Subsection III-C. In that scenario, transmission from v_0 to v_2 is over 5 hops. Suppose that each hop has the same priority, each loses CCH once followed by one successful re-transmission. Based on the distances between the vehicles in the example, the total communication delay $\tau > 1.5$ second. The simulation shows that the minimum distance between v_2 and v_1 approaches to 0, leading to a case of collision.

VII. Concluding Remarks

Intrinsic relationships between platoon control and communications introduced in this paper represent a new framework for intelligent highway transportation systems. As a first step in this direction, this paper is focused on establishing the key structure, the main algorithms, and interactions between the communication delay and vehicle platoon safety control. There are many important and intriguing issues left open for further exploration. Communication package drop rate, jitter, and emerging communication scheduling algorithms will be of interests. Furthermore, we have only considered basic driving conditions: Straight lanes, dry surface, good weather conditions, and no lane changes or platoon re-formation after vehicle departure or addition. All these issues are worth further studies.

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