Communication Information Structures and Contents for Enhanced Safety of Highway Vehicle Platoons

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***Abstract*—Highway platooning of vehicles 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 information structures and contents on platoon safety. By comparing different information structures which combine front sensors, rear sensors, and wireless communication channels, and different information contents such as distances, speeds, and drivers' actions, we reveal a number of intrinsic relationships between vehicle coordination and communications in platoons. Typical communication standards and related communication latency are used as benchmark cases in our study. The findings of this paper provide useful guidelines in sensor selections, communication resource allocations, and vehicle coordination.**

***Index Terms*—Highway platoons, vehicle safety, communication systems, communication latency, autonomous vehicles.**

I. Introduction

Highway platooning of vehicles has been identified as a promising framework in developing intelligent transportation systems [1], [2]. 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. In a platoon formation and maintenance, high-level distributed supervisors adjust vehicle spatial distributions based on inter-vehicle information such that roadway utilization is maximized while the risk of collision is minimized or avoided. Controllers at vehicle levels, sensors, and communication systems interact intimately in vehicle platoon formation and control. This paper investigates several key issues in such interactions.

Platoon control has drawn substantial attention lately [3], [4]. During the 90s, there were substantial contributions on platoon control, including PATH projects [5], [6], FleeNet, among others. Intelligent platoon control algorithms were introduced with demonstration and experimental validation [7], [8]. The most common objectives in platoon control are safety, string stability, and team coordination [9], [10]. Early studies of platoon control were not communication focused, due to less-advanced communication systems at that time. In our recent work [11], [12], a weighted and constrained consensus control method was introduced to achieve platoon formation and robustness. At present, on-board front radars are used in vehicle distance measurements. [12] employs convergence rates as a performance measure to evaluate benefits of different communication topologies in improving platoon formation, robustness, and safety.

Communication channels insert new dynamic subsystems into control loops. Impact of communication systems on feedback loops can be treated as added uncertainty such as delays and errors [13], [14], [15]. In terms of coordination of control and communication systems in a platoon, some intrinsic questions arise: (1) How much improvement of safety can be achieved by including communication channels? (2) What information should be communicated? What are the values of such information? (3) How will communication uncertainties such as latency, packet loss, and error affect safety?

This paper aims to answer these questions with quantitative characterization. To facilitate this exploration, we consider various information structures: (1) front radars only, (2) combined radars and wireless communications. In addition, we investigate the information contents: (1) distances only, (2) distance and speed, (3) additional early warning of the driver's braking action. Typical communication standards such as IEEE 802.11p and related communication latency are used as benchmark cases in this study. The findings of this paper will be useful to guide design of information infrastructures, information contents, control strategies, and resource allocations in platoon control problems.

The rest of the paper is organized into the following sections. Section II introduces the basic platoon control problem and safety issues. Section III defines control strategies and sets up evaluation scenarios for comparative studies of different information structures and contents. Our studies start with safety analysis in Section IV. Under some simplified scenarios, basic relations are derived, including speed-distance relationship for safe stopping distance and collision avoidance, distance progression in a platoon, and delay-distance functions

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for communication latency. Section V details typical communication scenarios. Communication latency characterization and related experimental data are presented. Section VI investigates impact of information structure by comparing radar-based distance sensing and communications. Front radars are the current commercial automotive technology. By expanding information structures to include wireless communication networks, improvement on safety is quantitatively studied. The roles of information contents are explored in Section VII, in which improvements on safety by including more information on vehicle speeds and drivers' actions are studied. Section VIII investigates impact of communication latency and uncertainties on vehicle safety. Typical scenarios of communication latency, radar resolution, and Doppler frequency shifting are considered. Finally, Section IX discusses implications of the results of this paper and points out some potential extensions.

II. Vehicle Dynamics and Platoon Information Structure

This paper is concerned with inter-vehicle distance control in a highway platoon. For clarity of investigation, we use simplified, generic, but representative vehicle dynamic models from [16]

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

where m (Kg) is the consolidated vehicle mass (including vehicle, passengers, etc.), v is the vehicle speed (m/s), $f(v)$ is a positive 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 $f(v) = av + bv^2$, 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 determined experimentally and approximately. This paper focuses on longitude vehicle movements within a straight-line lane. Thus, the vehicle movement is simplified into a one-dimensional system.

Vehicles receive platoon movement information by using sensors and communication systems. We assume that radars are either installed at front or rear of the vehicle. The raw data from the radars 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, radar information is limited to distances. In contrast, a communication channel from vehicle i to vehicle j can transmit any information that vehicle i possesses. We consider the following information contents for transmission: (1) vehicle i's distance that is measured by its front sensor, (2) vehicle i's speed, which is available by its own speedometer, (3) vehicle i's braking action. Information structures are depicted in Fig. 1. A vehicle may receive information from its front distance 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.

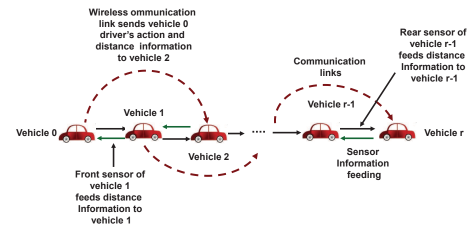

Fig. 1. Information structures.

For concreteness, we 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 baseline safety metric for comparison with other information structures. "Information Structure (b)" provides both front and rear distances. Then "Information Structure (c)" expands with wireless communication networks.

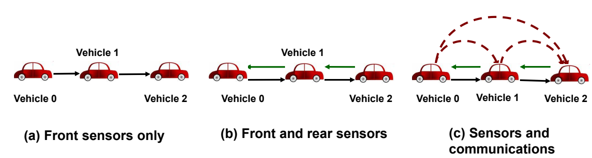

Fig. 2. Three main information structures: (a) Only front distance information is available for vehicle control. (b) Both front and rear distances are available. (c) Additional information is transmitted between vehicles.

Although we employ a three-car platoon for simplicity, it forms a generic base for studying platoon safety issues for more general platoons. This is graphically explained in Fig. 3. Here the vehicles in between the leading vehicle and the vehicle of interest are grouped as one sub-platoon. We treat this sub-platoon as one vehicle and this leads to the generic structure of Fig. 2. This also implies that the communication distance between the two vehicles may be high.

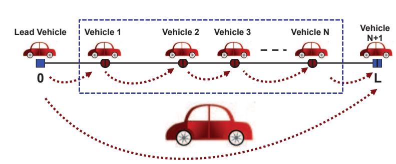

Fig. 3. Grouping vehicles.

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

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

where F_0 is the leading vehicle's driving action. F_1 and F_2 are local control variables. Since the vehicle lengths are fixed and can be subtracted from distance calculations, in this formulation a vehicle is considered as a point mass without length.

III. Control and Evaluation Scenarios

A. Feedback Control

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

There are numerous vehicle control laws which have been proposed or commercially implemented [17], [18]. Since the focus of this paper is on impact of information structures and contents rather than control laws, we 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 (small slope) and an enhanced braking region of a sharp nonlinear function towards the maximum braking force, as shown in Fig. 4. We denote this function as $F = g_1(d)$.

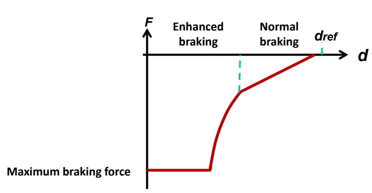

Fig. 4. Braking functions based on distance information.

Similarly, if vehicle i's speed information is transmitted to another vehicle j (behind i), the receiving vehicle can use this information to control its braking force. 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 $F = g_2(v_j - v_i)$, shown in Fig. 5.

B. Evaluation Scenarios

To investigate impact of information structures and contents on platoon safety, we need a reasonable platform to comparative studies. Since vehicle safety involves so many factors, we must define a highly simplified platform in which only

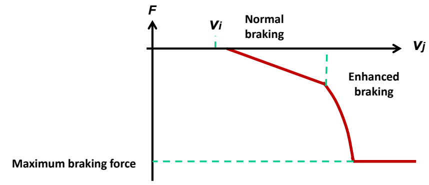

Fig. 5. Braking functions based on speed information.

key elements are represented. For this reason, we define the following basic scenarios.

We use some typical vehicle data from [16]. Under the MKS (metre, kilogram, second) system of units, the vehicle mass m has the range $1400 - 1800$ Kg, the 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.

Three identical cars form a platoon as in Fig. 2. The vehicle masses are $m_0 = m_1 = m_2 = m = 1500$ Kg. The aerodynamic drag coefficients $b_0 = b_1 = b_2 = 0.43$. The nominal inter-vehicle distance $d_{ref} = 40$ m. The cruising platoon speed is 25 m/s (about 56 mph). The road condition is dry and the maximum braking force 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 feedback control function $F = g_1(d)$ is depicted in Fig. 6. The actual function is

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

where $d_{ref} = 40$ (m), $k_1 = 50$, $k_2 = 4$, $F_{max} = 10000$ (N). The function applies smaller braking force when the distance is only slightly below the reference value, but increases the braking force more dramatically in a nonlinear function when the distance reduces further until it reaches the maximum braking force. We comment that if one views the braking function purely from safety aspects, it is desirable to impose the maximum braking as soon as the distance drops. This, however, will compromise drivability and smoothness of platoon operation. In fact, the braking function of Fig. 6 is already on the aggressive side.

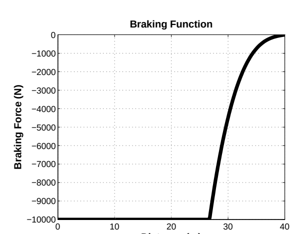

Fig. 6. Braking function for Example 4.

To see this, consider the slow braking condition: Suppose that the leading vehicle applies a braking force 1000 N, which brings it to a stop from 25 m/s in 37.5 second. The distance trajectories of d_1 and d_2 are shown in Fig. 7. In this case, the minimum distances are 30.9 m for d_1 and 24.2 m for d_2. This is acceptable for safety. On the other hand, the transient period shows oscillation, indicating that the braking action has been aggressive already under normal driving conditions.

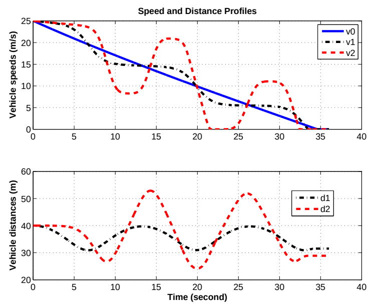

Fig. 7. Distance trajectories under slow braking.

For evaluations, we will use the fast braking scenario defined as follows.

Fast Braking: The leading vehicle uses a braking force 5000 N. If the cruising speed of the platoon is 25 m/s, then this braking force brings the leading vehicle to a stop from 25 m/s in 7.5 second.

In some derivations, we also use the extreme case in which the maximum braking force 10000 (N) is applied. This is for the worst-case analysis. But the Fast Braking case is representative for understanding safety issues. In this paper, the minimum vehicle distance $d_{min} = 15$ (m) is used to distinguish "acceptable" and "unsafe" conditions. When a distance is reduced to 0, a collision occurs.

IV. Safety Analysis

We conduct safety analysis under the scenario specified in Section III-B. Some simplifications will be made so that explicit expressions can be derived to clarify the main underlying safety issues.

We observe that under this braking force, the influence of the tire/road resistance and aerodynamic drag force bv^2 is relatively small. a is proportional to the tire deformation and inversely proportinal to the radius of the loaded tire. The rolling resistance of a normal car 1500 kg on convrete with rolling coefficient 0.01 can be estimated:

$$F_r = 0.01(1500kg)(g) = 0.03(1500kg)(9.81m/s^2) = 147(N), \tag{4}$$

When $b = 0.43$ and $v = 25$ m/s, the aerodynamic drag force is 268.75 (N). This is only 8.3% of the braking force. In the subsequent development, we omit the aerodynamic drag force in our derivations, but include it in all simulation studies.

Assuming that the platoon cruising speed is $v_0(0) = v_1(0) = v_2(0) = 25$ (m/s) and the leading vehicle brakes at $t = 0$ with $F_0 = -\alpha$, where α is a constant (for the Fast Braking, $\alpha = 5000$ (N); and the worst-case $\alpha = F_{max} = 10000$ (N)). The braking function (3) is used. It follows that the dynamics of the three-car platoon are

$$\begin{cases} \dot{v}_0 &= -\frac{\alpha}{m} \\ \dot{v}_1 &= -\frac{g_1(d_1)}{m} \\ \dot{v}_2 &= -\frac{g_1(d_2)}{m} \\ \dot{d}_1 &= v_0 - v_1 \\ \dot{d}_2 &= v_1 - v_2, \end{cases} \tag{5}$$

with the initial conditions $v_0(0) = v_1(0) = v_2(0) = 25$ (m/s) and $d_1(0) = d_2(0) = d_{ref} = 40$ (m).

A. Safety Regions

In a platoon, usually vehicle 2 acts later than vehicle 1 due to information cascading structures (vehicle 1 sees the slowdown of the leading vehicle before vehicle 2). Suppose that after vehicle 1 applied the maximum braking force at an earlier time, vehicle 2 starts to apply the maximum braking force at t_0.

Theorem 1: Assume that $v_1(t_0) < v_2(t_0)$. Denote $\eta = v_2^2(t_0) - v_1^2(t_0)$, and $\delta = d_2(t_0)$. The final distance is

$$d_2^{final} = \delta - \frac{\eta m}{2F_{max}}.$$

Proof: For $t \geq t_0$, the two vehicles have the dynamics $\dot{v}_1 = -\frac{F_{max}}{m}$, $\dot{v}_2 = -\frac{F_{max}}{m}$, which implies $v_1(t) = v_1(t_0) - \frac{F_{max}}{m}(t - t_0)$, $v_2(t) = v_2(t_0) - \frac{F_{max}}{m}(t - t_0)$.

Vehicle 1 stops after travelling the total stoping time $v_1(0)m/F_{max}$ and the total length $\Delta_1 = v_1^2(t_0)m/(2F_{max})$. Similarly, the total length travelled by vehicle 2 to a complete stop is $\Delta_2 = v_2^2(t_0)m/(2F_{max})$. Thus, the final distance is

$$d_2^{final} = \delta - \frac{(v_2^2(t_0) - v_2^1(t_0))m}{2F_{max}} = \delta - \frac{\eta m}{2F_{max}}.$$

□

For any given final distance $d_2^{final} = C$, the function

$$\eta = \frac{2F_{max}}{m}(\delta - C)$$

defines the iso-final-distance line on the $\delta - \eta$ space, shown in Fig. 8, in which the acceptable region and collision avoidance region are also marked.

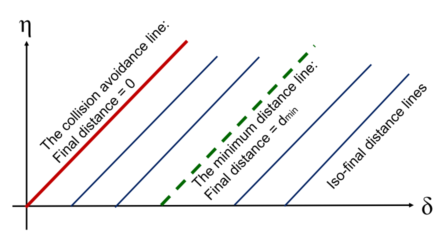

Fig. 8. $\delta - \eta_v$ lines under a given final distance. Acceptable safety regions and collision avoidance regions can be derived from such curves.

B. Platoon Distance Progression

A platoon consists of many vehicles. Under typical information structures, there is a phenomenon of inter-vehicle distance progression that must be considered in platoon management.

Assumption 1: (1) At $t = 0$, the platoon of n following vehicles is at the cruising condition with equal distance d_{ref} and speed $v(0)$. (2) The information on the braking action $F_0 = -F_{max}$ of the leading vehicle at $t = 0$ is passed to the following vehicles in a progressive manner: For $t > 0$, $F_1(t) < F_2(t) < \cdots < F_n(t)$, except when the braking forces reach the saturation values -10000 (N), in which case, one may have $F_1(t) = F_2(t)$, etc. (3) Suppose that vehicle j starts to apply the maximum braking force at t_j. We assume that $t_1 < t_2 < \cdots < t_n$.

Theorem 2: Under Assumption 1, the total travel length L_j of vehicle j before a complete stop satisfies

$$L_0 = \frac{v(0)m}{2F_{max}} < L_1 < L_2 < \cdots L_n.$$

The minimum final distance is

$$\min_{j=1,\ldots n} d_j^{final} = d_{ref} - \max_{j=1,\ldots,n} (L_j - L_{j-1}).$$

Proof: The expression $L_0 = \frac{v(0)m}{2F_{max}}$ is proved in Theorem 1.

Let the braking force for vehicle j be $-f_j(t)$ with $f_j > 0$. The speed profile is

$$v_j(t) = v(0) - \int_0^t \frac{f_j(\tau)}{m} d\tau.$$

The total travel time T_j satisfies

$$\int_0^{T_j} \frac{f_j(\tau)}{m} d\tau = v(0).$$

The total length travelled by vehicle j until a complete stop is

$$L_j = \int_0^{T_j} v_j(t)dt = v(0)T_j - \int_0^{T_j} \int_0^t f_j(\tau) d\tau dt.$$

Under Assumption 1, we have the inequalities

$$v_1(t) < v_2(t) < \cdots < v_n(t), t > 0 \tag{6}$$

which implies that

$$T_1 < T_2 < \cdots T_n. \tag{7}$$

These imply

$$L_1 < L_2 < \cdots L_n.$$

Now, the final distance d_j^{final} is

$$d_j^{final} = d_{ref} - (L_j - L_{j-1})$$

which implies that

$$\min_{j=1,\ldots,n} d_j^{final} = d_{ref} - \max_{j=1,\ldots,n} (L_j - L_{j-1}).$$

This completes the proof. □

C. Delay-Distance Relationship

This paper concentrates on communication latency and its impact on vehicle safety. In this subsection, a relationship between the communication delay time and its detrimental effect on inter-vehicle distance is derived. To single out the delay effect, we impose the following assumption.

(1) Direct Transmission of Braking Action

Suppose that the leading vehicle transmits its braking action directly to the vehicle behind it. This is the fastest way to inform the following vehicle to take action. If no time delay is involved, then the following vehicle will brake immediately and the inter-vehicle distance will be kept contact until both vehicles come to the complete stop. However, communication delays will postpone the following vehicle's action. The main question is: How much delay can be tolerated?

Assumption 2: (1) The leading vehicle and following vehicle travel at the cruising condition with distance d_{ref} and speed $v(0)$. (2) The information on the braking action $F_0 = -F_{max}$ of the leading vehicle at $t = 0$ is immediately transmitted to vehicle 1 with a communication delay τ. (3) No other information is available to vehicle 1.

Theorem 3: Under Assumption 2, the final distance d_1^{final} is

$$d_1^{final} = d_{ref} - v(0)\tau + \frac{F_{max}}{2m}\tau^2.$$

Proof: Since the braking force for the leading vehicle is $-F_{max}$, its speed profile is

$$v_0(t) = v(0) - \frac{F_{max}}{m} t.$$

At time τ, its speed is

$$v_0(\tau) = v(0) - \frac{F_{max}}{m}\tau.$$

Vehicle 1 receives the braking information at τ and immediately applies the maximum braking force $-F_{max}$ with the initial speed $v(0)$. As a result, $\eta = v^2(0) - v_0^2(\tau)$.

By Theorem 1, the final distance is

$$\begin{aligned} d_1^{final} &= d_{ref} - \frac{\eta m}{2F_{max}} \\ &= d_{ref} - \frac{(v^2(0) - v_0^2(\tau))m}{2F_{max}} \\ &= d_{ref} - \frac{(v^2(0) - (v(0) - \frac{F_{max}}{m}\tau)^2)m}{2F_{max}} \\ &= d_{ref} - \frac{(2v(0)\frac{F_{max}}{m}\tau - \frac{F_{max}^2}{m^2}\tau^2)m}{2F_{max}} \\ &= d_{ref} - v(0)\tau + \frac{F_{max}}{2m}\tau^2. \end{aligned}$$

□

Corollary 1: For a given required minimum distance d_{min}, the maximum tolerable communication delay is

$$\tau_{max} = \frac{v(0) - \sqrt{v^2(0) - 2\frac{F_{max}}{m}(d_{ref} - d_{min})}}{2}.$$

Proof: By Theorem 3, to satisfy $d_1^{final} \geq d_{min}$, the maximum tolerable τ is solved from $d_{min} = d_{ref} - v(0)\tau + \frac{F_{max}}{2m}\tau^2$ or

$$\frac{F_{max}}{2m}\tau^2 - v(0)\tau + (d_{ref} - d_{min}) = 0$$

whose smaller solution is

$$\tau_{max} = \frac{v(0) - \sqrt{v^2(0) - 2\frac{F_{max}}{m}(d_{ref} - d_{min})}}{2}.$$

□

In particular, for collision avoidance, $d_{min} = 0$ and we have

$$\tau_{max} = \frac{v(0) - \sqrt{v^2(0) - 2\frac{F_{max}}{m}d_{ref}}}{2}.$$

For the evaluation scenario in Section III-B, $v(0) = 25$, $F_{max} = 10000$, $m = 1500$, $d_{ref} = 40$, and $d_{min} = 15$. The corresponding maximum tolerable delay is $\tau_{max} = 3.9609$ second. For collision avoidance, $d_{min} = 0$ and $\tau_{max} = 7.7129$ second.

However, if the vehicle weight is increased to $m = 1800$ (Kg) and the platoon cruising distance is reduced to $d_{ref} = 30$, the tolerable delay is reduced to $\tau_{max} = 1.7956$ second.

Typical vehicle braking control must balance safety and driveability. Consequently, inter-vehicle distances may reduce more significantly than the scenario of this subsection. As a result, the maximum tolerable delay may be significantly less. These will be evaluated in the subsequent case studies.

(2) Broadcasting Schemes and Consequence

The leading vehicle's braking action can be broadcasted to the platoon. The average communication latency depends on the distance between the sending (leading vehicle) node and the receiving node. Using the basic square relationship, if the first following vehicle experiences a delay $\tau_1 = \tau$, then the second vehicle will have a delay around $\tau_2 = 4\tau$, the third vehicle with $\tau_3 = 9\tau$, and so on.

For example, if $d_{ref} = 40$ (m) and $\tau_1 = 100$ (ms), then $\tau_2 = 400$ (ms) (at 80 (m)), . . ., $\tau_7 = 4.9$ (s) (at 280 (m)), which implies that d_7 will fall below 15 m, violating the minimum distance requirement.

This analysis indicates that communication schemes need to be carefully designed when a platoon has many vehicles.

V. Communication Systems

A. Communication Standards and Latency

To study more realistically how communication systems and control interact, we use a generic communication scheme shown in Fig. 9. In this scheme, a data packet is generated and enters the queue for transmission. The queuing time depends on network traffic and data priorities. The packet contains both data bits and error checking bits. We assume that the error checking mechanism is sufficient to detect any faulty packet. If the packet transmission is successful, the receiver returns an acknowledgment message to the sender, which completes the transmission. If the packet is received with error, it will be discarded and a request is sent back to the sender to re-transmit the same packet. The permitted total time for transmission of a packet is pre-determined by the control updating times. If a packet was not successfully transmitted when the control updating time is up, the packet will be considered as lost.

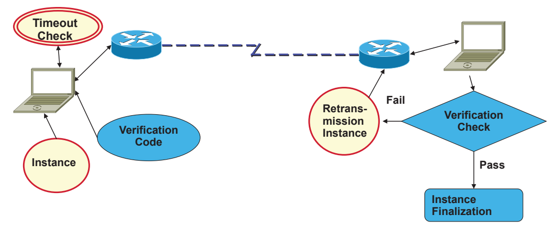

Fig. 9. Data transmission schemes.

Inter-vehicle communications (IVC) can be realized by using infrared, radio, or microwaves waves. For instance, in IEEE 802.11p, a bandwidth 75 MHz is allotted in the 5.9 GHz band for dedicated short range communication (DSRC) [19], [20]. Alternatively, ultra-wideband (UWB) technologies have been used for IVC. IEEE 802.11x, where $x \in \{a, b, g, p \ldots\}$ have been studied for inter-vehicle use. At present, many applications use DSRC with IEEE 802.11p (a modified version of IEEE 802.11 (WIFI) standard) at the PHY and MAC layers. 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 service. In the network service, users have a choice between the wireless access for vehicle environments short message protocol (WSMP) or the internet protocol version 6 (IPv6) and user datagram protocol (UDP)/transmission control protocol (TCP). Single-hop messages typically use the bandwidth-efficient WSMP, while multi-hop packets use the IPv6+UPD/TCP for its routing capability.

Inter-vehicle communications use wireless networks that are subject to severe uncertainties. For example, the signal-to-interference-plus-noise ratio (SINR) [21] attenuates with distance (it decreases inverse proportionally to the cubic of the distance between the two vehicles). It is also affected by obstructions such as buildings, bridges, other vehicles, etc. Other factors include queue delays, network data traffic conditions, routes, signal fading, signal interference from other vehicles, Doppler shifts, and traffic and weather conditions. These uncertainties depend significantly on channel coding schemes and communication networks. These factors collectively determine packet delivery delays, packet loss rates, etc. This paper will focus on delay effects. To be concrete in treating communication systems, we will employ IEEE 802.11 standards as our benchmark systems and the related latency data [19].

Bandwidth-delay product is often used to characterize the ability of a network pathway in carrying data flows [22], [23]. When the TCP protocol is used in data communications, packet-carrying capacity of a path between two vehicles will be limited by this product's upper bound. For more detailed discussions on capacity/delay tradeoffs, the reader is referred to [19] and the references therein. Note that latency is further caused by delays in each hub's queues, routes (multi-hub), packet delivery round-trip time, channel reliability, retransmission, scheduling policies in interference avoidance strategies. Although typical transmission delays can be as low as several millisecond, vehicular traffic scenarios introduce combined latency of several hundreds of milliseconds even several seconds. In this paper, we will show that delays of such scales will have significant impact on vehicle safety.

B. A Single-Hop Experimental Study

We assume the three-vehicle scenario in 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 direct control of 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. Fig. 10 sketches some of the time delays from these steps.

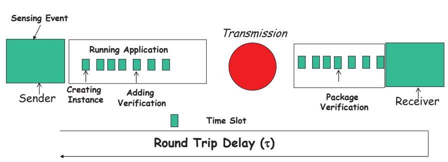

Fig. 10. A Round Trip Delay.

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 Package Delivery Rate(PDR) is 1, the RTT $\tau^0 \leq 100$ ms since IEEE 1609.4 specifies the reoccurrence of the CCH at the rate of every 100 ms.

The physical limitations on wireless channels (bandwidth and power constraints, multi-path fading, noise and interference) present a fundamental technical challenge to reliable high-speed communication. One or several retransmissions are often necessary to meet a PDR requirement. In this case, delay is $\tau = n\tau^0$ where n is the number of average rounds for a successful transmission. In the following examples, we show how modulation rates and channel interferences affect the number of retransmission and delay τ. Due to the network system heterogeneity and highway environments, we are using the truth-ground data, rather than ns-3 simulations.

Example 1: [25] reports experimental data of IEEE 802.11p DSRC from a team of vehicles driving on certain Michigan highways. Package Delivery Rates (PDR) are measured under different driving conditions, traffics, and surroundings. A typical curve from [25] is re-generated in Fig. 11. When the modulation rate is 6 Mbps, the Package Delivery Rate (PDR) is about 75% at a distance of 85 m. The first round-trip takes about 100 ms. Each subsequent round-trip must catch the next CCH and it takes on average more than three retransmissions to achieve a PDR over 98.5%. Consequently, the average delay is $\tau \approx 0.3$ second. When the modulation rate is increased to 18 Mbps, the PDR is reduced to 36% at 85 m. In order to meet the same PDR 98.5%, the delay is more than 1 second.

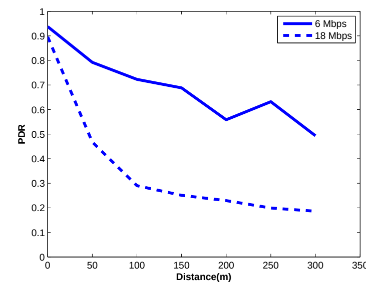

Fig. 11. PDR vs. separation distance under different data rates in the Rural Road (RR) environment (with 95% Confidence Interval). Here, the data rates are 6 Mbps and 18 Mbps. The transmission power is 20 dBm.

Example 2: In this experimental study, we use the IEEE 802.11g standard to analyze the affects of multi-path interference. The communicating nodes reside on laptop computers and are moved from a short distance of 20 m to 95 m. In the first experimental setting, the transmission pathway does not have obvious obstacles, except low grass on the open field. Communication latency is recorded by the synchronized clocks on these computers. Fig. 12 provides the experiment data on recorded latency for different inter-node distances. A simplified curve can be obtained by data fitting, which is also shown in the same figure. It is noted that latency between 100 ms to 600 ms is typical in this case study.

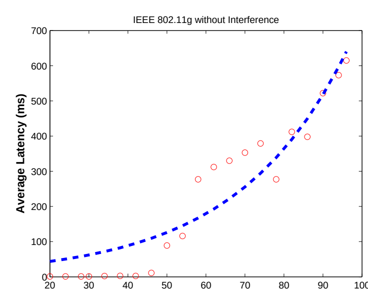

Fig. 12. Dependence of latency on distance without obstacles on the transmission pathway.

Example 3: Extending on the experiment in Example 2, we now evaluate impact of obstacles on transmission pathways. Under the same experimental protocols as in Example 2, we select a field with many trees, but not overly dense. Consequently, depending on distances, the transmission pathways are obstructed by several trees. Fig. 13 demonstrates the experimental data on communication latency under different transmission distances. It is seen clearly that with obstacles, communication latency increases significantly to a range of 3.4 second.

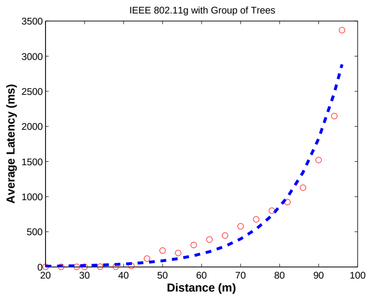

Fig. 13. Dependence of latency on distance with trees on the transmission pathway.

C. Multi-Hop Communication Data

Inter-vehicle communications may involve multi-hops which create further delays. Typically, the IPv6+UDP/TCP protocols can be used in such systems. Unlike the WSMP protocols which use 11 bytes overhead, the IPv6 protocol 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 and highway environment. Since we are only concerned with latency data, we quote here the studies in [19] that contain extensive experimental results. A typical curve from [19] is re-generated in Fig. 14. 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.

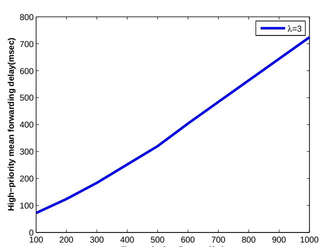

Fig. 14. Average delay of high-priority message dissemination for 5 hops of communication as functions of the transmission range.

VI. Platoon Information Structure

A. Safety under Front Sensor Information

We start with the basic information structure of using front distance sensors only. For the three-car platoon in Fig. 2 and the control law $F = g_1(d)$ in Fig. 4, the closed-loop system becomes

$$\left\{ \begin{array}{rcl} \dot{v}_0 & = & \frac{1}{m_0}(F_0 - (a_0 v_0 + b_0 v_0^2)) \\ \dot{v}_1 & = & \frac{1}{m_1}(g_1(d_1) - (a_1 v_1 + b_1 v_1^2)) \\ \dot{v}_2 & = & \frac{1}{m_2}(g_1(d_2) - (a_2 v_2 + b_2 v_2^2)) \\ \dot{d}_1 & = & v_0 - v_1 \\ \dot{d}_2 & = & v_1 - v_2 \end{array} \right. \quad (8)$$

Example 4: We consider the scenario defined in Section III-B. Suppose that the platoon uses only front sensors to measure inter-vehicle distances, namely the information structure (a) in Fig. 2 is in effect. The feedback control function $F = g_1(d)$ is depicted in Fig. 6. We will use the following fast braking condition for comparison.

Under the **Fast Braking** scenario from Section III-B, 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. The distance trajectories of d_1 and d_2 are shown in Fig. 15. In this case, the minimum distances are 20.6 m for d_1 that 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 in the top plot of Fig. 15 that since vehicle 2 relies on d_2 to exercise its braking control function, there is a dynamic delay in initiating its braking. d_2 is reduced to about 20 m when vehicle 2 starts to act. For a large platoon, this dynamic delay from vehicle to vehicle is a serious safety concern.

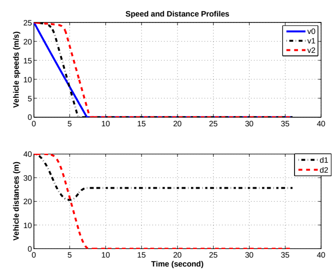

Fig. 15. Distance trajectories under fast braking.

B. Adding Distance Information by Communications

We next expand on the information structures beyond front sensors by adding distance information by communications.

Example 5: Continuing from Example 4, 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; the maximum braking force is 10000 N.

Under the **Fast Braking** scenario as in Example 4, suppose now that vehicle 1 sends d_1 information to vehicle 2 by communication. As a result, vehicle 2 can use both d_1 and d_2 in its control function; see Fig. 16.

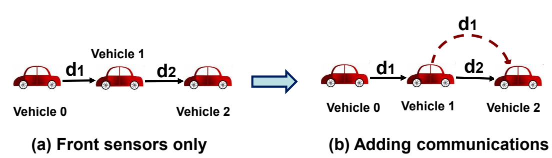

Fig. 16. Enhanced information structure by sending d_1 to vehicle 2 by communication links in Example 5

Suppose that vehicle 2 modifies its braking control function from the previous $F_2 = g_1(d_2)$ to the weighted sum $F_2 = 0.5g_1(d_2) + 0.5g_1(d_1)$ that uses both distances. The resulting speed and distance trajectories are displayed in Fig. 17. Now, the minimum distances are 20.6 m for d_1 and 15.9 m for d_2, both are within the safety region.

To compare Fig. 15 and Fig. 17, we note that with information feeding of d_1 into vehicle 2, vehicle 2 can slow down when d_1 is reducing before d_2 changes. Consequently, it is able to act earlier, resulting in a reduced distance swing for d_2 during the transient.

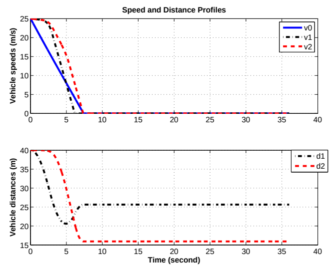

Fig. 17. Distance trajectories when the distance information d_1 is made available to vehicle 2. It shows improvement over Fig. 15.

VII. Platoon Information Contents

A. Adding Speed Information by Communications

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

Example 6: For the same three-car platoon under the same initial conditions as Example 5, we add the leading vehicle's speed v_0 into the information structure. This information is transmitted (or broadcasted) to both vehicles 1 and 2. Under the **Fast Braking** scenario as in Example5, suppose that vehicles 1 and 2 receive the additional speed information v_0, resulting in a new information structure shown in Fig. 18.

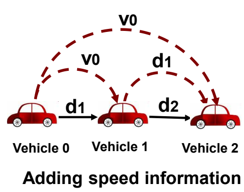

Fig. 18. Enhanced information structure by sending d_1 to vehicle 2 and v_0 to both vehicles 1 and 2.

From the control functions of Example 5, additional control actions $g_2(v_0, v_1)$ and $g_2(v_0, v_2)$ are inserted. The resulting speed and distance trajectories are displayed in Fig. 19. Now, the minimum distances are 28.3 m for d_1 and 27.1 m for d_2, a much improved safety performance.

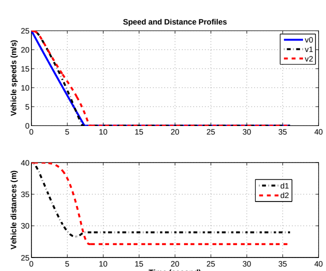

Fig. 19. Distance trajectories when both distance and speed information is made available.

B. Adding Braking Event Information by Communications

Intuitively, if the leading vehicle's braking action can also be communicated, the following vehicles can act much earlier than their measurement data on vehicle movements. To evaluate benefits of sending the driver's action, we add the braking event information of the leading vehicle to vehicle 2 by communications.

Example 7: For the same three-car platoon under the same initial conditions as Example 6, we now further add the leading vehicle's braking event information F_0 into the information structure. To understand the impact, we purposely assume that vehicle 1 does not receive this information. In other words, this information will be transmitted only to vehicle 2 by communications. Under the **Fast Braking** scenario as in Example 6, suppose that vehicle 2 receives the additional braking event information F_0, resulting in a new information structure shown in Fig. 20.

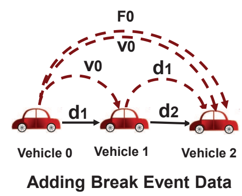

Fig. 20. Enhanced information structure by sending the braking event F_0 to vehicle 2.

From the control functions of Example 6, an alternative control action F_0 is inserted when $d_2 < d_{ref} = 40$ m. The resulting speed and distance trajectories are displayed in Fig. 21. Now, the minimum distances are 28.3 m for d_1 and 30.6 m for d_2, a much improved safety over the case in Example 6. It is interesting to note that by knowing the leading vehicle's action, vehicle 2 can react faster than even vehicle 1 which does not receive the braking action data.

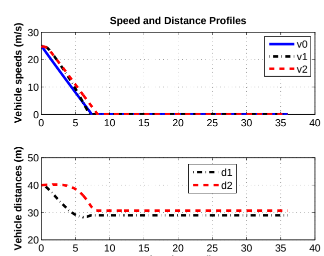

Fig. 21. Distance trajectories with added braking event information.

VIII. Impact of Radar and Communication Uncertainties

A. Impact of Radar Resolution and Missed Detection

Radar sensors provide a stream of measurement data, typically using 24, 35, 76.5, and 79 GHz radars. In general, radar sensor measurements are influenced by many factors that limit their accuracy and reliability. These include signal attenuation by the medium, beam dispersion, noises, interference, multi-object echo (clutter), jamming, etc.

We first consider the impact of radar's resolution on a platoon system. Within the same setup as Example 5, vehicle 2 receives the distance information of d_1 and d_2 in which d_2 is measured by a radar. Taking into consideration radar resolution, the measured distance is $\tilde{d}_2 = d_2 + \gamma\delta$, where γ is a resolution level and δ is a standard Gaussian noise $\mathcal{N}(0, 1)$.

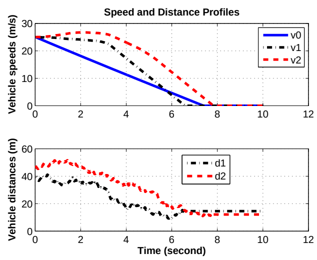

Fig. 22. Distance trajectories under a radar of low resolution (1 m).

Fig. 22 shows a simulation result under a radar of resolution 1 m. The distribution of the minimum distances after repeated runs to account for randomness is shown in Fig. 23. Although the expectation is 8.01 m, the minimum distance has a high probability of having values close to zero. Consequently, this low resolution radar is not suitable for this application.

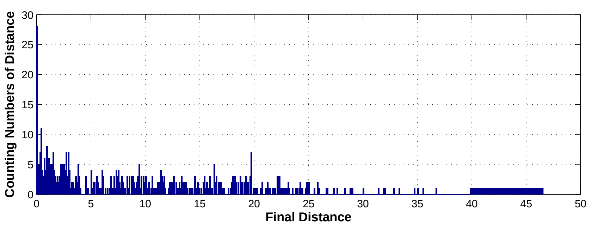

Fig. 23. The distribution of minimum distances d_2 under a radar of low resolution (1 m).

Next, we upgrade the radar to a higher resolution 0.1 m. A corresponding simulation is shown at Fig. 24. The minimum distances for both d_1 and d_2 are much improved. The distribution of minimum distances of d_2 is shown in Fig. 25. The random minimum distances have expectation 15.92 m and variance $\sigma^2 = 0.31$. This is an acceptable resolution for this application.

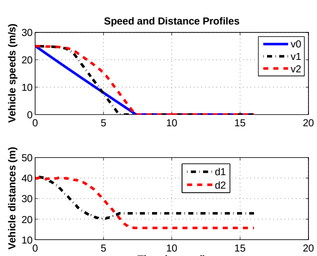

Fig. 24. Distance trajectories with high Resolution Radar.

It is noted further that uncertainties of radar signals include also random false alarms or missed detection. In this scenario,

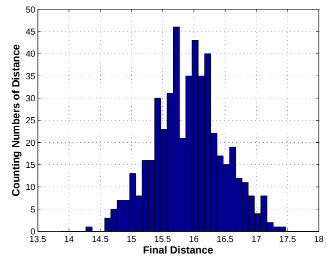

Fig. 25. Distance Distribution of d_2 with high Resolution Radar .

the sensor does not provide information at the sampling time, and the control/brake action must rely on its previous measurements and other available information from different resources. This situation is similar to Example 12 when communication information is unavailable, which will be detailed in the next subsection.

B. Impact of Communication Delay

Communications introduce a variety of uncertainties. Most common types are communication latency and packet loss. These can be caused by many factors as listed in Section I. This paper focuses on communication latency. Depending on environment and communication protocols, communication latency can be near a constant, distance dependent, or random. We cover these cases in the following subsections.

1) Fixed Delays: We first consider fixed delays.

Example 8: Under the same system and operating condition as Example 5, we assume that the communication channel for the distance information has a delay of τ second. The impact of the communication delay is shown in Fig. 26. Without the 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.

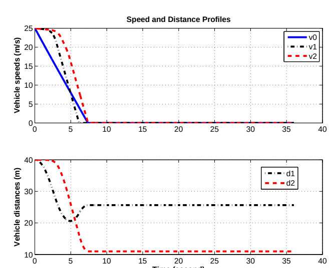

Fig. 26. Distance trajectories when communication delays are considered.

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

Next, we use experimental delay data in our simulation studies.

Example 9: Under the same system and operating condition as Example 5, we assume that communication systems use the single-hop scenario in Section V-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. Many factors affect such delays. One essential consideration is channel capacity. Shannon's channel capacity claims that if the channel is too noisy which reduces channel capacity, information cannot be effectively transmitted. This is translated into very large channel latency under a required PDR. In this sense, impact analysis of channel latency is in fact a study on communication resources. Here we use platoon safety as a performance criterion in this study.

2) Distance-Dependent Delays: In vehicle platoon environment, communication latency depends directly on inter-vehicle distances. These are reflected clearly in Figures 11, 12, and 13. It is observed that during platoon formation and braking, inter-vehicle distances change substantially. This subsection considers delays as a function of distance.

Example 10: Under the same system and operating condition as Example 9, we now use more realistic experimental data in Fig. 12 for latency which is a function of distance. Based on the relationship of distance and latency, the simulation in Fig. 27 shows that the minimum distance for d_2 is now 12.7 m. Furthermore, if signal interference, obstructions, and fading are considered, the latency is increased to these in Fig. 13. The simulation results in a minimum distance for d_2 as 5.6 m. This is shown in Fig. 28, which causes safety concerns.

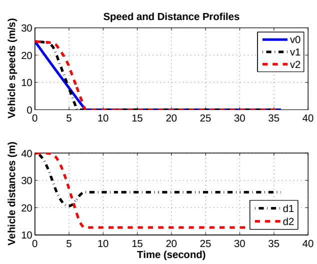

Fig. 27. Distance trajectories when communication delays are dependent on vehicle distances, whose function form is given in Fig. 12 for the "no obstacle" scenario.

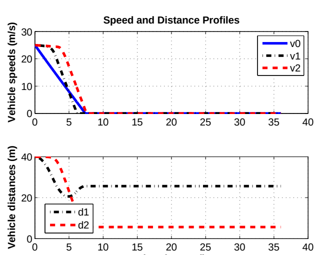

Fig. 28. Distance trajectories when communication pathways are obstructed as shown at Fig. 13.

Example 11: Continuing the study of Example 9, we consider the multi-hop scenario in Subsection V-C. In that scenario, transmission from v_0 to v_2 is over 5 hops. Suppose that each hop has the same priority, and that 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 for d_2 approaches to 0, leading to a collision.

3) Random Delays: Typically, communication delays are random variables with certain distributions. Depending on latency control mechanisms of transmission protocols, the latency can have different distributions. We use the common Gaussian distribution for our study in this subsection.

Example 12: Assume that communication latency is a random variable, due to the random features of wireless transmissions. In this example, we model τ as a random variable that is Gaussian distributed with $\mathbb{E}(\tau) = 1.2$ (second) and variance $\sigma^2 = 0.09$. Continuing the study of Example 11, the simulation in Fig. 29 shows that the minimum distance d_2 approaches to 5.09 m.

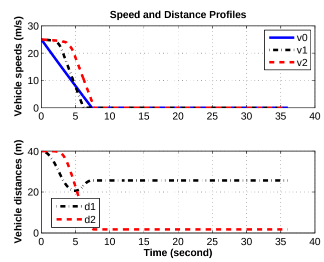

Fig. 29. Distance trajectories under communication latency which is Gaussian distributed.

Simulation results of minimum distance distribution are shown at Fig. 30. The variance of d_2 is $\sigma^2 = 0.142$.

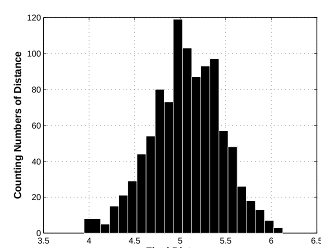

Fig. 30. Distance distribution of d_2 under random communication latency .

C. Impact of Doppler Frequency Shift and Signal Spreading

Mobility-induced Doppler spread is one of the main factors that degrade the performance of Orthogonal Frequency Division Multiplexing (OFDM) schemes. It introduces Inter-Symbol Interference (ISI) and Inter-Carrier Interference (ICI) by destroying the orthogonality between adjacent sub-carriers.

In most cases, DSRC is adequate in restoring both zero ISI and zero ICI in highly mobile, severe-fading vehicular environments, as discussed with great detail in [24]. In the physical layer of IEEE 802.11p, the bandwidth of each DSRC channel is 10 MHz, which entails less ISI and ICI than IEEE

802.11a which uses 20 MHz channel bandwidth. This brings better wireless channel propagation with respect to multi-path delay spreads and Doppler effects caused by high mobility and roadway environments. Also, DSRC expands Guard Band (GB) to 156 KHz and has $1.6\mu s$ guard interval for OFDM schemes. The Guard Band between sub-carriers can ensure that mobility-induced Doppler spreads do not cause two adjacent sub-carriers to overlap.

On the other hand, with high operation frequency at 5.9 GHz, IEEE 802.11p is subject to higher Doppler frequency shifts. When vehicle speeds are extremely high (such as 250 km/h on German highways), the issue of Doppler frequency shifts become more pronounced. At present, fast network topology switching and complicated road environments are still challenges with respect of ISI and ICI, and remain to be resolved by new technologies.

Fig. 31, re-produced from [25], compares the impacts of Open Field (OF) and Rural Freeway (RRF) on the PDR. The PDR remains nearly unchanged in the OF environment when relative vehicle velocities vary from 0 (m/s) to 25 (m/s). In contrast, the PDR drops dramatically in the RRF environment. For example, when the relative velocity is 12.5 (m/s), the PDR of the communication link in the RRF environment is reduced to $1/3$ of that with the OF environment. This implies that in the RRF environment, much more communication resources are needed to ensure the same level of safety. As a result, it is advisable that these DSRC characteristics be incorporated into the platoon design by VANET designers.

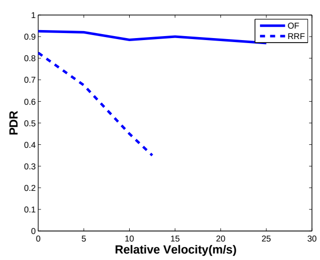

Fig. 31. The impact of relative velocities on the PDR(with the 95% confidence interval). A bin of 20 packets is used to calculate PDR values as well as relative velocities.

D. System Integration with VANET Framework

The generic platoon model of this paper is an important component of a VANET framework as shown in Fig. 32. In our exploration, the actual communication routes are not specified. Within a VANET, the links among vehicles can be realized by V2V communications or V2I pathways involving access points, wireless towers and other infrastructures. Our model provides a fundamental framework to study impact of communications on vehicle safety and can be specified to different communication configurations. The findings of this paper can be used as guidelines in selecting VANET parameters. For example, transmission power, modulation rate, and coding scheme can be selected so that they meet the requirements of an acceptable minimum inter-vehicle distance. Also, a platoon can potentially enhance VANET data access performance. By using vehicles as transmission hubs, data can be replicated and relayed to more vehicles in the group. This structure improves VANET resources in a distributed manner and, if used properly, can improve overall performance.

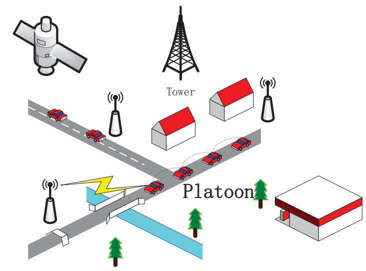

Fig. 32. System integration of a platoon with a VANET framework.

While this paper is focused on one platoon formation, a platoon experiences many dynamic variations in real implementations. These include lane change, vehicle departure and addition, platoon reformation, etc. At the network level, such changes amount to network topology variations. At the communication/physical level, some uncertainties will be introduced such as echo among vehicles and road infrastructures. A VANET can easily accommodate such topology changes by using vehicle IDs and their links. Furthermore, by seamless integration into a VANET, a platoon can have access to VANET resourses, including GPS, Internet, distributed live database, VANET-enabled applications, etc. Consequently, a platoon can potentially utilize additional information in its safety considerations via inter-vehicle communications and emission reduction via traffic information. These topics are, however, beyond the scope of this paper. We refer the reader to [26], [27] for some related studies.

IX. Discussions and Concluding Remarks

This paper investigates the interaction between control and communications, in the framework of highway platoon safety. Information structure, information content, and information reliability have been taken into consideration in this study. It is well perceived that communication systems introduce uncertainties that are of many types and values. To be concrete, we have selected communication latency as a key uncertainty in this study.

The main results of this paper demonstrate that communications provide critical information that can enhance vehicle safety effectively beyond distance sensors. In fact, from our simulation studies, platoon control may mandate communications for additional information. Although traditionally, distance and vehicle speed are immediate candidates for transmission, our results show that drivers' braking events contain very effective information for platoon management. Our simulations suggest that platoon communications place event data under more prominent considerations.

Our study shows that communication latency is a critical factor in information exchange. Large latency can diminish values of data communication in platoon control. It is a common framework in multi-vehicle communication scenarios that vehicles within an interference radius do not transmit simultaneously. A direct consequence is that latency becomes larger. For instance, under the IEEE 802.11p standard, transmission radius can reach 1 km. If 50 vehicles are in this region and each transmission (or broadcasting) takes 30 ms, a delay of 1.5 second will occur between consecutive transmissions of a given vehicle. Our study shows that such a delay has an alarmingly high impact on vehicle safety. This issue deserves further studies.

What is reported in this paper is a first step in this direction. There are many un-resolved issues. We are currently investigating the impact of communications on platoon safety under packet erasure channels. Furthermore, we have only considered basic driving conditions: Straight lanes, dry surface conditions, good weather conditions, and no lane changes or platoon re-formation after vehicle departure or addition. System integration with VANET framework is a worthy topic to pursue. All these issues are worth further studies.

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