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A Method for the Rapid Propagation of Emergency Event Notifications in a Long Vehicle Convoy

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Abstract: Convoys composed of autonomous vehicles could improve the transportation and freight industries in several ways. One of the avenues of improvement is in fuel efficiency, where the vehicles maintain a close following distance to each other in order to reduce air resistance by way of the draft effect. While close following distances improve fuel efficiency, they also reduce both the margin of safety and the system's tolerance to disturbances in relative position. The system's tolerance to disturbances is known as string stability, where the error magnitude either grows or decays as it propagates rearward through the convoy. One of the major factors in a system's string stability is its delay in sending state updates to other vehicles, the most pertinent being a hard braking maneuver. Both external sensors and vehicle-to-vehicle communication standards have relatively long delays between peer vehicle state changes and the information being actionable by the ego vehicle. The system presented here, called the Convoy Vehicular Ad Hoc Network (Convoy VANET), was designed to reliably propagate emergency event messages with low delay while maintaining reasonable channel efficiency. It accomplishes this using a combination of several techniques, notably relative position-based retransmission delays. Our results using Network Simulator 3 (ns3) show the system propagating messages down a 20-vehicle convoy in less than 100 ms even with more than a 35% message loss between vehicles that are not immediately adjacent. These simulation results show the potential for this kind of system in situations where emergency information must be disseminated quickly in low-reliability wireless environments.

Keywords: vehicular ad hoc network; vehicle-to-vehicle communication; intelligent transportation system; string stability

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1. Introduction

The push toward an Intelligent Transportation System (ITS) requires all vehicles to be capable of communicating important information with surrounding vehicles. This information can be as mundane as a turn signal or as important as a stopped vehicle on a highway. While fully autonomous vehicles are not yet commonplace, various ITS systems can be used to enable semi-autonomous convoys of vehicles that use a human driver as a leader with mostly autonomous vehicles that follow it. This kind of arrangement is especially beneficial in the trucking industry for various reasons. The global trucking industry is experiencing a shortage of drivers [1], and the ability to move more freight with fewer drivers could alleviate the issue. Adding to this, when a truck convoy uses a short following distance, the draft effect can decrease fuel consumption by up to 4% for the leader and 11% for the followers [2–5]. While vehicle convoys can provide many benefits, they also come with many challenges.

1.1. String Stability

The main challenge facing vehicle convoys is a phenomenon known as string stability. Typically, a convoy of vehicles tries to maintain a certain headway distance or time between each other using sensors such as radar. If a vehicle experiences a disturbance in its velocity (such as applying the brakes), then the vehicles behind it apply actuations according to their control law to regain the nominal headway. If the disturbance is large enough or fast enough, then it may send the system into an unstable region, depending on various factors. A familiar example of string instability is in “phantom traffic jams”, where small decreases in the speed of a leader can cause follower vehicles to overcorrect. This, in turn, causes even greater overcorrection as the “wave” propagates rearward to the point that some vehicles may come to a complete stop on a highway. In short, this is a problem of delays. Even if the system could instantaneously recognize and decide upon an appropriate course of action, there are still unavoidable delays in vehicle actuation. The follower vehicle’s sensors only notice a change after the leader vehicle’s actuation delays have concluded. Thus, when considering its own actuation delays, the follower has less time to react and so may need to apply a higher magnitude control input compared to the leader. If the follower could be informed of the leader’s actuation intent at the time that the decision is made, then the effect of actuation delays can be largely negated. At this point, the problem becomes one of communication delay. While this work does not address how communication delays affect a string-stable controller design, there is a wealth of prior research on this type of problem. Seiler et al. discussed the general effects of string stability in a vehicle platoon that is controlled using a fixed inter-vehicle spacing [6]. Their findings showed that disturbance sensitivity increases for rearward vehicles when only information on the immediate neighbor is known, such as only using sensors or only having communication with the vehicle’s immediate leader. Only upon incorporating information on the behavior of the ultimate leader did the sensitivity decrease further down the platoon. Fernandes et al. created a more real-world style of experiment by directly addressing communication delays, among other things [7]. In particular, they utilized anticipatory information broadcast (what a vehicle plans to do in the near future), a fully non-overlapping transmission schedule, and synchronized vehicle actuation to maintain the stability of the platoon. The most relevant aspect here is in how heavily the platoon leader’s information is weighted in the follower’s controller. When the leader’s information has no effect outside its immediate follower, the platoon displays instability. The platoon becomes stable when the leader’s information is almost exclusively used. Zheng et al. discussed how a vehicle platoon’s internal stability is affected by communication topologies and the vehicles’ inertial delays [8]. While their work did not specifically deal with string stability, it did show how delays in information flow dramatically change the characteristics of the vehicle platoon. In their results, the topologies that do not incorporate a direct link to the leader result in much greater spacing errors further rearward in the platoon when a disturbance occurs, as compared to topologies that do incorporate a link to the leader. Ning and Lin worked toward finding string stability even when communication delay is randomly distributed [9]. What they showed is a method for determining a minimum headway time that guarantees string stability given a certain packet delivery probability. Specifically, their method allows for a certain percentage of message delays to be greater than a threshold value while still maintaining string stability. This work is pertinent here in that it shows how smaller inter-vehicle spacings become feasible as the delays become shorter and more consistent. Samii and Bekiaris-Liberis developed a linear predictor-feedback cooperative adaptive cruise control (LPF-CACC) that is robust to communication delays [10]. Of importance to us is their graphs that show how communication delays affect the region of parameters that guarantee string stability. As they increased the communication delay, the region shrinks, meaning more parameter sets are now string unstable. As with Ning and Lin, Samii and Bekiaris-Liberis also showed that there is a clear tradeoff between allowable communication delay and headway time. This further reinforces the idea that a lower communication delay allows for tighter vehicle platoons. Lastly, Tian et al. performed a similar analysis by performing a numerical analysis of a CACC vehicle platoon to show how string stability is affected by different parameter changes [11]. One set of graphs showed the string-stable set of control gains for different constant communication delays. The volume of the "stable body" as they called it shrinks considerably as the communication delay increases beyond 0.1 s. They later showed how spacing and speed errors propagate rearward through the platoon for different communication delays. In short, the lower the communication delay, the faster the error attenuates as it propagates rearward. When given a communication delay such that the control gains are on the edge of the stable region, the spacing and speed errors remain constant as they propagate rearward.

1.2. Communication Protocols

String stability issues can be mitigated or even eliminated if the information delay between the leader and the followers is reduced. This can be accomplished by proactively informing the surrounding vehicles of actuation events as soon as the decision is made. Without loss of generality, we will assume that the primary actuation of interest is a braking event. SAE J2945/1 defines the communications for on-board vehicle-to-vehicle (V2V) systems [12]. Note that SAE J2945/1B is the standard governing Class 8 vehicles such as tractor trailers, but it defers to SAE J2945/1 for BSM communication scheduling It defines, among other things, the schedule for Basic Safety Message (BSM) transmission for each vehicle. A BSM contains information on the overall vehicle state as well as any high-importance events. However, even if SAE J2945/1 is used, there can be up to 0.1 s of delay before transmitting a BSM that says a hard braking event is occurring. To make matters more difficult, there is no guarantee that the BSM is received. If the wireless communication channel is unreliable, then the overall delay between event and message reception may be much higher. While SAE J2945/1 has mechanisms in place for estimating the probability of a remote vehicle's reception of a transmission, it does not allow BSM transmissions to occur any more frequently than 10 Hz.

1.3. Communication Channels

Generally, the wireless channel in vehicular environments can be characterized using a combination of log-distance power loss and Nakagami fast fading. As a brief summary, log-distance states that receive power drops as a function of distance to the power of n, and Nakagami said that received power is randomly distributed more widely as the value of m decreases. Thus, a high probability of high received power over distance means a low log-distance n and high Nakagami m values. Molisch et al. stated that for light traffic on a highway, the log-distance characterization parameter n generally falls between 1.8 and 1.9, with crowded highways generally having higher values [13]. Molisch also stated that the fast-fading Nakagami m factor was usually 3–4 for short distances and less than 1 for long distances. Viriyasitavat et al. made similar findings, saying that the log-distance n could vary between 1.6 and 2.9 on the highway, 2.3 and 3.5 in suburban environments, and 1.8 to 3.4 in urban environments [14]. Cheng et al. focused on the 5.85–5.925 GHz range for their study and found similar results to those of Molisch with regards to the Nakagami m factor [15]. They found that m would typically be around 3 to 4 over a 0 to 5 m distance, while dropping below 1 at 70 to 90 m. Together, these findings imply that longer distance direct communications can be more challenging and much less predictable than shorter-range communications.

1.4. Ad Hoc Routing Protocols

Many would point to dedicated infrastructure, primarily cellular towers, as the solution to vehicular message dissemination. While current and future cellular infrastructure could be used for this task, it may not always have the capacity, latency, or (most importantly) coverage to guarantee safety-critical communication. A potential solution could be the use of ad hoc wireless networks, where participating devices take on the additional responsibility of routing messages for those that do not share a direct communication link.

When applied to vehicles, this idea is known as a vehicular ad hoc network (VANET). While there is a large body of work on standardizing the wireless communication systems for vehicles (e.g., IEEE P1609), a standard for vehicular ad hoc routing has yet to be established. Thus, finding an effective and efficient routing scheme for VANETs has become the work of a large body of prior research. Li and Wang wrote a survey paper discussing the various types of routing protocols for VANETs [16]. Their findings indicate that standard ad hoc routing protocols such as AODV and DSR are typically unsuitable for VANETs (see Section 3.3 for our tests on the matter). They mention geographic routing (using physical location to decide on the next hop) and cluster-based routing (recognizing groups of vehicles and assigning a "head" for each) among others as being attempts at solving the routing problem. A direct attempt at formulating a VANET routing protocol was made by Koubek et al. with their "Vehicular Reactive Routing" system [17]. The system was designed around the IEEE P1609 protocol stack and utilizes slightly modified versions of the existing messages. The relevant part of their system is in the retransmission choice mechanism. Every node that hears a packet being broadcast will decide on a backoff timer for retransmission. The timer was designed such that the node closest to and with the most similar motion to the destination will have the shortest timer and thus retransmit first. A similar backoff timer system was used by Sasaki et al. for the purposes of removing neighbor discovery beacons in VANETs [18]. In their system, the rebroadcast delay is set purely based on proximity to the destination. The common thread in both systems is the use of "eavesdropping" to inform each node on the necessity of their retransmission, thus enhancing channel efficiency. Koubek primarily used the backoff timer as an arbitration mechanism, while Sasaki at least mentioned the benefits of redundant transmission paths. Lastly, Liu et al. approached the problem of safety message dissemination in an urban environment using clustering and vehicle movement prediction [19]. They recognized that infrastructure nodes will likely not be able to provide sufficient coverage to alert every vehicle of safety-critical information when and where it is needed. Their system constructs a "core" network of vehicles based on the vehicles' trajectories in order to improve communication coverage. To find this set of vehicles, the initiator sends a request indicating the region of interest for the safety message. The surrounding vehicles scale the delay of their responses to this request based on the similarity of their trajectories with respect to the region of interest. After the core vehicles are chosen by the initiator, those vehicles then repeat the process until as much of the region of interest is covered as possible. What many of the protocols mentioned here have in common is their use of backoff timers as more than just a message collision avoidance mechanism. Retransmission or response delays can be used to implicitly convey information about some relationship between the communicating vehicles, such as fitness toward a purpose.

2. Problem Statement

While other works in the area of VANETs work around random movements and reasonably reliable communication channels, our work focuses on the opposite. Our goal was to create a message dissemination system that is fast and reliable in the face of an unreliable communication channel by leveraging the assumptions provided with a convoy of vehicles. Specifically, our goals were as follows:

1. Eventual Consistency. There should be no dropped messages.
2. Speed of Dissemination. Ideally, it should propagate a message through the convoy in less than 100ms (the minimum delay between BSM transmissions).
3. Channel Efficiency. The number of additional transmissions and the amount of extra data attached to existing transmissions are minimized.

3. Simulation Environment and the Convoy VANET System

We used Network Simulator 3 (ns3) as our simulation environment, specifically version 3.31, as this work was started in 2020. We will refrain from listing any exact parameter values here, as they will be listed in Section 4 along with the list of experiments performed.

3.1. Simulated Wireless Channel

We used ns3's included YANS Wifi Physical and YANS Wifi Channel to simulate the physical layer of the channel. The propagation loss model was the combination of the log-distance, Nakagami, and range cutoff values. Range cutoff was added to eliminate extremely low probability events from affecting the results. In addition, ns3's included constant speed propagation delay model was used, though this choice has little effect on the simulation's fidelity. The simulated wireless channel was designed to be less reliable compared to the findings listed in Section 1.3. This was done for two reasons. First, we wanted to show the performance of our system in a degraded communication environment. Second, we wanted to reduce the number of simulated vehicles, as it would otherwise require a longer transmission distance to reach the desired reliability degradation. The issue of string stability still exists whether each "entity" is one vehicle or multiple all moving in unison due to being within the high-reliability transmission region of the leader. The approximate reception reliability vs. distance for the default parameter set is listed in Table 1.

Table 1. Approximate reception reliability vs. distance for the default wireless channel parameters.

Distance	Approximate Reception Reliability
10 m	95%
30 m	85%
60 m	65%
90 m	30%
120	15%
150	5%
More than 200 m [1]	0%

[1] The hard cutoff for the range was set at 200 m.

3.2. Simulated Wireless Procotol

The lower layers of the network protocol consist of ns3's included QoS WAVE MAC, 802.11p, and Internet stacks. These three stacks use default parameters aside from 802.11p, and we used OFDM 12 Mbps and 10 MHz instead of 6 Mbps. This change should have no effect on the end result; it is only included for completeness. Every vehicle in the simulation has a unique IP address on the same subnet.

3.3. OLSR and AODV

To form a point of comparison for the effectiveness of the Convoy VANET System, we initially chose to test against two popular ad hoc routing protocols: Optimized Link State Routing (OLSR) [20] and Ad hoc On-demand Distance Vector (AODV) [21]. These two protocols represent the typical forms of proactive and reactive approaches to ad hoc routing, respectively. The intention was to compare these two protocols against Convoy VANET in aspects such as message delay and route maintenance overhead. The experiment setup is similar to the experiments conducted on the Convoy VANET system; most importantly, the vehicles were spaced 30 m apart to induce an approximate 85% reception reliability. The only differences are that the convoy was only ten vehicles long (instead of 20) and the head of the convoy was unicasting its message to the last vehicle in the convoy (as opposed to broadcasting). The lack of broadcast is because OLSR and AODV do not handle broadcasts particularly well in ns3, and at this stage of the work, the experiment was meant to be a first pass at obtaining a point of comparison. The results of this experiment lend credence to the statements of Li and Wang in that normal routing protocols are ill suited for VANETs [16]. In short, both OLSR and AODV failed to reliably propagate packets down a ten-vehicle convoy. The packet delivery ratio to the last vehicle was consistently well under 50%, with ratios as low as 10% being not uncommon. When it did manage to deliver a packet, it would occasionally be delayed by as much as one full second, which is obviously unacceptable. The exact results of these tests are not shown primarily because of the lack of nuance and useful information. Also, this particular experiment is simple enough to build for oneself using the simulation parameters provided throughout Section 3.

The reason why OLSR and AODV ultimately failed is due to the fact that they do not have any substantial reception reliability mechanisms. This is understandable given that they exist at the network layer of the typical OSI or TCP/IP stack instead of the transport layer. If we had added reliability guarantees using TCP instead of UDP, then we would have also foregone the ability to broadcast the messages at the transport layer (unless we make significant modifications to TCP). One could argue that transmission eavesdropping could still occur with TCP and that the participatory devices could still exchange data fragments until all have received the message. However, this approach only moves the problem up to the application layer, and the process for the efficient exchange of the eavesdropped data would still need to be defined.

3.4. Convoy VANET System

The purpose of the convoy VANET system is to quickly and efficiently disseminate Safety Messages (SM) to all vehicles in the convoy. An SM can be any highly time-sensitive piece of information, but here, we considered it to be a hard braking maneuver. To accomplish this goal, the Convoy VANET system included a few independent components. The most important component is the routing choice method. In essence, the routing system is a combination of traditional ad hoc routing schemes and the methods proposed by Koubek and Sasaki. When a node decides to (re)transmit an SM it will decide upon a preferred retransmitter (PRTX). This choice of PRTX will be listed in the SM and read by all that receive the message. If the designated PRTX receives the SM, it will retransmit the SM immediately. Every other node that receives the SM will decide on a retransmission delay that is based on its physical distance to the designated PRTX (if it is known). If a node hears that the SM has been retransmitted by a rearward peer, then it cancels its queued SM retransmissions to reduce the number of unnecessary retransmissions. After the initial "wave front" of transmissions, the nodes will be listening for any peers that did not receive the SM and then attempt to rectify the situation. The goal of this type of system is for the SM to have the opportunity to move as quickly as possible down the convoy, even if it is not received by every node on the first pass. The remaining details will be described in the following subsections.

3.4.1. Senders

Every node contains at least one sender: the vehicle state (VS) sender. This sends information analogous to a BSM: position, velocity, and heading. This information is sent every 100 ms plus a random delay between 0.01 ms and 0.50 ms. The start time for every node's sender is randomly offset by a value between 0 s and 1 s. The randomness on the timings is mainly to prevent transmission collisions due to the perfect synchronization that is possible in a simulation. See the paragraph regarding the routing output function in Section 3.4.3 for additional information regarding the VS message transmissions.

The lead node contains an additional sender: the SM sender. An SM is a set of data that we are trying to propagate quickly, such as indicating a hard braking maneuver. The sender is initialized with a schedule of SMs to send at various times. For the tests described below (Section 4) a new SM is sent every 5 s starting at 20 s into the simulation. Upon starting an SM sending event, the SM sender will attempt to broadcast the SM every 10 ms, only stopping on the 10th transmission. However, the routing protocol will determine if the SM needs to actually be sent (see Section 3.4.3).

3.4.2. Receivers and Data Storage

Every node contains a receiver for handling VS messages. The only purpose of the receiver is to save incoming VS messages into the node's internal storage for later use. Specifically, VS messages are used to determine a node's distance to every other node that it has received VS messages from. As detailed in Section 3.4.3, physical distance is used for tasks such as determining a retransmission delay for a received SM.

3.4.3. Routing Protocol

The routing protocol is the main contributor of the Convoy VANET system's behavior. The routing protocol's major components are reliability mapping, preferred retransmitter updating, delayed SM scheduling, output routing, and input routing.

Reliability mapping is simply the periodic check of how many VS messages have been received compared to how many should have been received. As VS messages are received, they are added to a map that is keyed off of the remote node ID. In this way, every vehicle is tracking the reception reliability between itself and every other vehicle. Outdated data are periodically pruned to prevent memory leaks. While this assumes symmetric channel reliability, it could be cumbersome in a real system to include reliability metrics in the state message (see Future Work, Section 7). These reliability metrics are used in the preferred retransmitter update.

Preferred retransmitters (PRTXs) are a part of the message propagation system. In short, a PRTX is a node that is designated by the original (re)transmitter to be the one that retransmits an SM as soon as they receive it. Every other node that hears an SM will set their retransmission delay according to various metrics outlined below. This idea is meant to be a hybrid between the retransmission delay systems of Koubek and Sasaki and the single-retransmitter systems used in most ad hoc routing protocols. The PRTX is chosen based on two metrics: distance and reliability. The PRTX is simply the node that is furthest rearward that maintains some minimum level of reception reliability. If no nodes meet the reliability requirement, the PRTX is set to null, meaning every node that hears the transmission will fall back onto the retransmission delay system, as outlined later. The PRTX is periodically updated based on the current reliability map.

The choice of retransmission delay is given by one of two equations. If the SM includes a PRTX and the node knows its location, then the delay is given by Equation (1):

$$d = (D * t_D) + r_{D,min} + (R_1 * r_{D,range}) + (R_2 * r_{S,range}) \quad (1)$$

where d is the total delay, D is the distance to the PRTX, t_D is the time per unit distance, $r_{D,min}$ is the random component minimum where distance is known, $r_{D,range}$ is the random component range where distance is known, $r_{S,range}$ is the random component range for adding an extra "small" amount of randomness, and R_1 and R_2 are uniform random variables between 0 and 1. Note, while the "small randomness" component could just as well be added to the other range components, it is possible in the code to disable its inclusion, and while this functionality is never used, it is included here for accuracy and completeness. Otherwise, the delay is purely random and given by Equation (2):

$$d = r_{R,min} + (R_1 * r_{R,range}) + (R_2 * r_{S,range}) \quad (2)$$

where $r_{R,min}$ is the random component minimum when the distance is unknown, and $r_{R,range}$ is the random component range when the distance is unknown. All other variables are the same as in Equation (1). After the delay is determined, the node checks its currently scheduled transmissions to ensure that no two occur within a certain amount of time of each other. This time amount is called the "transmission keep-out" time (see Section 4). Any SM transmissions that fall within the keep-out time of another will simply be dropped.

Every packet created by a node passes through the output routing function. In the case of the leader sending an SM, it checks whether this SM has been confirmed as having propagated rearward. If it has not propagated rearward, then the function adds the current choice of PRTX to the packet and allows it to be sent. If the SM is confirmed as having propagated rearward, then the function does not allow the packet to be sent (see Section 3.4.1). If the message is a VS, then it attaches a list of the most recently received SMs and allows the packet to be sent. Note that the SM list does not include the entire

SM but merely an identifying value for each one. This is to reduce the amount of data added to the VS message. The received SM list is used by other nodes as a confirmation of reception. If the VS's sender is behind the receiving node, then this confirmation is also proof of rearward propagation. Hearing a rearward node's retransmission of an SM is the other method of confirming rearward propagation.

Every packet received by a node passes through the input routing function. While the input routing function handles both VS and SM packets, VS packets are simply stripped of their SM lists and then handed off to the receiver (see Section 3.4.2). Received SM lists are handled by Algorithm 1. Received SMs are handled by Algorithm 2. Note, in Algorithm 1, the for-each loop uses the set difference operation in its check, meaning that it is executing for every SM we have received thus far but not including every SM the sending node has listed as received.

Algorithm 1: Handler Function for Received SM List

```
L ← SM list from sending node
P ← position of sending node, if known
R ← SM list for ego node
if P is known and rearward then
    foreach s ∈ L do
        Mark s as having propagated rearward
        Cancel any cancellable scheduled retransmissions of s
    end
end
foreach m ∈ R \ L do
    if P is known then
        r ← number of retransmissions such that there is at least a 90% chance of at
          least one being received, up to a maximum of 6
    else
        r ← 4
    end
    Schedule r uncancelable retransmissions of m with delays based on P
end
```

Algorithm 2: Route Input Function for SM

```
S ← received SM
if S is an SM we have not seen before then
    Add S to our list of SMs
end
if S has not propagated rearward then
    Set S.PRTX to our choice of PRTX
    if we are the original PRTX for S then
        Retransmit S immediately
    end
    Schedule 3 retransmissions of S with delays based on the original PRTX
      location
end
if S has propagated rearward AND we have not recorded this fact then
    Record S as having propagated rearward
    Cancel any cancellable scheduled retransmissions of S
end
```

4. Experiment Parameters and Tests

There are three parameter sets and four spacing scenarios for a total of 12 experiments. The Standard parameter set is the basic setup that generally produced favorable results over the course of development. The Double-Delay parameter set tests the effects of a larger overall delay on retransmissions. To this end, it uses values for the various delay parameters (such as $r_{D,min}$ and $r_{R,range}$) that are twice as large as those in the Standard parameter set. Note that both the minimum values and the random ranges are doubled in the Double-Delay set. The Double-Random parameter set was used to test the effects of larger random ranges on the retransmission delay, while having the same minimum values as the Standard set. Thus, the minimum delay values are unchanged compared to the Standard set while the random range components are all doubled. There were a total of 20 nodes in the simulation. The Standard, Close, and Far spacing scenarios placed the nodes 30 m, 10 m, and 60 m apart, respectively. The Far-to-Close spacing scenario starts the nodes at 60 m apart and moves them to be 10 m apart by the end of the simulation. The first SM is sent at 20 s so the system has some time to stabilize, with a new SM occurring every 5 s thereafter for a total of 20 safety events. Table 2 lists the parameter values used for the experimental simulations. The parameter abbreviations are as follows:

- p_{PRTX}: Minimum reception probability to be eligible as a PRTX.
- t_D: Delay time per unit distance for distance-based SM delays; see Equation (1).
- $r_{D,min}$: Random component minimum for distance-based SM delays; see Equation (1).
- $r_{D,range}$: Random component range for distance-based SM delays; see Equation (1).
- $r_{R,min}$: Random component minimum for non-distance-based SM delays; see Equation (2).
- $r_{R,range}$: Random component range for non-distance-based SM delays; see Equation (2).
- $r_{S,range}$: Random component range for small extra SM delays; see Equations (1) and (2).
- t_K: Transmission keep-out time; only one SM transmission may occur within this amount of time.
- LD_n: Path loss exponent for log-distance loss model.
- LD_d: Reference distance for log-distance loss model.
- LD_l: Reference loss for log-distance loss model.
- $Naka_{d1}$: Nakagami loss model distance 1.
- $Naka_{d2}$: Nakagami loss model distance 2.
- $Naka_{m0}$: Nakagami loss model m value for distances from 0 to $Naka_{d1}$.
- $Naka_{m1}$: Nakagami loss model m value for distances from $Naka_{d1}$ to $Naka_d2$.
- $Naka_{m2}$: Nakagami loss model m value for distances from $Naka_{d2}$ and beyond.

Table 2. Experiment parameter variations.

	Standard	Double Delay	Double Random
p_{PRTX}	0.70	0.70	0.70
t_D	0.02 ms/m	**0.04 ms/m**	0.02 ms/m
$r_{D,min}$	0.00 s	0.00 s	0.00 s
$r_{D,range}$	1.0 ms	**2.0 ms**	**2.0 ms**
$r_{R,min}$	2.5 ms	**5.0 ms**	2.5 ms
$r_{R,range}$	2.5 ms	**5.0 ms**	**5.0 ms**
$r_{S,range}$	1.0 ms	**2.0 ms**	2.0 ms
t_K	1.0 ms	1.0 ms	1.0 ms
LD_n	2.00	2.00	2.00
LD_d	1.00 m	1.00 m	1.00 m
LD_l	58 dB	58 dB	58 dB
$Naka_{d1}$	5.00 m	5.00 m	5.00 m
$Naka_{d2}$	101.00 m	101.00 m	101.00 m
$Naka_{m0}$	2.00	2.00	2.00
$Naka_{m1}$	0.65	0.65	0.65
$Naka_{m2}$	0.50	0.50	0.50

Bold values are different from those in the Standard set.

5. Results

Figures 1–27 illustrate the simulation results. For the bar and whisker plots, the red center line represents the median, the blue box is the range of the 25th and 75th percentiles, the dashed lines extend to the minimum and maximum that are not considered outliers, and the red crosses are outliers. The reception delay bar and whisker plots show the range of delays before each node first receives an SM. The number of safety transmissions bar and whisker plots show the range of the number of SM transmissions each node makes in propagating each SM. The 3D bar plots for the number of SM transmissions display the same data as their corresponding bar and whisker plots, except the additional axis separates the data by the time of the corresponding SM event (called the SM Initial Send Time). This means that the 3D bar plots can show how many times each node transmitted during each SM event. The 3D bar plots for the reception delay (Figures 21, 24 and 27) show the same information as their corresponding bar and whisker plot, except for the additional axis for the SM event, similar to the number of transmissions, 3D bar plots. Note that all graphs use the same scale for the vertical axis (i.e., reception delay or number of transmissions) for consistency.

5.1. Known Behavioral Anomalies

In most of the plots showing number of retransmissions, node 19 (the one at the end of the convoy) is shown to consistently transmit more than the others (see Figures 8, 10 and 12). This is because node 19 is effectively unaware that it is the end of the convoy. Because there is no rearward peer to retransmit the SM to (which would cause node 19 to cancel its pending retransmissions), it simply continues retransmitting until the retransmission counter hits zero. This issue was deemed a low priority as it is isolated to a single node and predictable due to its position. Nevertheless, it is still mentioned in the Future Work section (Section 7). The similarly high transmission numbers of node 0 are discussed in Section 5.3.

5.2. General Trends and Analysis

The Convoy VANET system generally works well at ensuring a quick propagation of SMs. The standard spacing scenarios consistently show less than 20 ms propagation times to the end of the convoy, even with a doubled delay and delay randomness (Figures 1, 3 and 5). All but the far-spacing plus doubled-delay situation (Figure 15) consistently resulted in propagation times lower than 0.10 s to the end of the convoy. The reception delay generally follows a linear trend outside the close-spacing situations (Figures 7, 9 and 11), and the number of SM transmissions are mostly consistent across the convoy (barring nodes 0 and 19 of course). The number of SM transmissions is typically reasonable given the channel reliability as well. For a 65% reliability link (i.e., a 60 m distance), it would require, on average, approximately 1.54 transmissions before the first successful reception. This means that there would be an average of approximately three transmissions for a successful single message exchange between two nodes. We see for the far-spacing situation that most of the nodes transmit between one and five times per safety event (see Figures 13, 15 and 17). The 3D bar plots show that for each safety event, there is a small subset of nodes that transmit much more than the others (e.g., Figures 2, 4 and 6). However, this subset typically changes for each safety event, leading to the bar and whisker plots showing an even distribution of high-transmission outliers (e.g., Figures 14, 16 and 18). Doubled delays tend to increase the reception delay while having a minimal effect on the number of transmissions. Doubled-delay randomness tends to not increase the reception delay at all over standard delays, while also not having a significant effect on the number of transmissions. The most significant factor in the number of transmissions and reception delay is spacing, which it is effectively a proxy for communication reliability. Close spacing results in many nodes receiving the first transmission, as seen by how the reception delays only increase marginally for the rearward nodes. Far spacing results in a wider variance of propagation delay as most receptions occur between immediate neighbors, leading to more opportunities for delays. The "far-to-close" spacing tests produce results that resemble a combination of all three fixed spacing tests. The reception delay plots in Figures 19, 22 and 25 show the higher-end tracking more closely to the far spacing tests and the lower-end tracking more closely to the standard- and close-spacing tests. The number of transmissions do not change much over the course of the vehicle movement, apart from the very last SM event at the closest distance having several non-transmitting nodes (Figures 20, 23 and 26). Of particular importance are Figures 21, 24 and 27. These figures illustrate the data contained in the reception delay plots in Figures 19, 22 and 25, respectively, but are here separated by SM events. They were included to show how the reception delay for each vehicle decreases as they move closer together. This highlights the Convoy VANET system's ability to adapt to changing scenarios, taking advantage of a more reliable communication channel to reduce propagation delay.

5.3. Outliers

Occasionally, there will be a node with a reception delay that is approximately 0.05 s to 0.10 s higher than that of its nearby peers. This occurs when an SM is transmitted but the skipped node does not receive it while a further node does. The further node then retransmits the SM, but againn the skipped node does not receive it while the original transmitter does, causing the original transmitter to recognize it as having propagated rearward. In assuming the skipped node does not receive the SM from any further rearward nodes' transmissions, it must now wait until a node hears its VS, which indicates that it has not heard the SM. At this point, the nearby nodes will begin transmitting the SM again, allowing it to be received. Because the VS is transmitted every 0.10 s, this situation will incur, on average, 0.05 s of extra delay.

A more common outlier is node 0 transmitting SMs much more than its followers (see Figure 12). When any node transmits more than 5 SMs, it is usually a consequence of hearing a VS message and scheduling uncancelable delayed SM transmissions. This is especially prevalent with node 0 because of simulation timing consistency. Node 0 always sends the SM on the exact 5 s division (20.000 s, 25.000 s, 30.000 s, etc.). If another node schedules its VS before the minimum delay afforded by the retransmission system, then node 0 will schedule several uncancelable SM retransmissions (see Section 3.4.3). Other nodes do not exhibit this behavior as consistently because the time at which they first receive an SM is largely random, as opposed to node 0's perfect consistency. This issue is not as prevalent with far spacing due to the lower reception reliability of VS messages, meaning only one node may trigger it semi-consistently instead of two or three. There is no mechanism in place to recognize the minimum amount of time needed before a confirmation of reception may be received (see Future Work, Section 7). While this issue may not be realistic, it was left in because it illustrates the main shortcoming of the system: the use of uncancelable SM retransmissions.

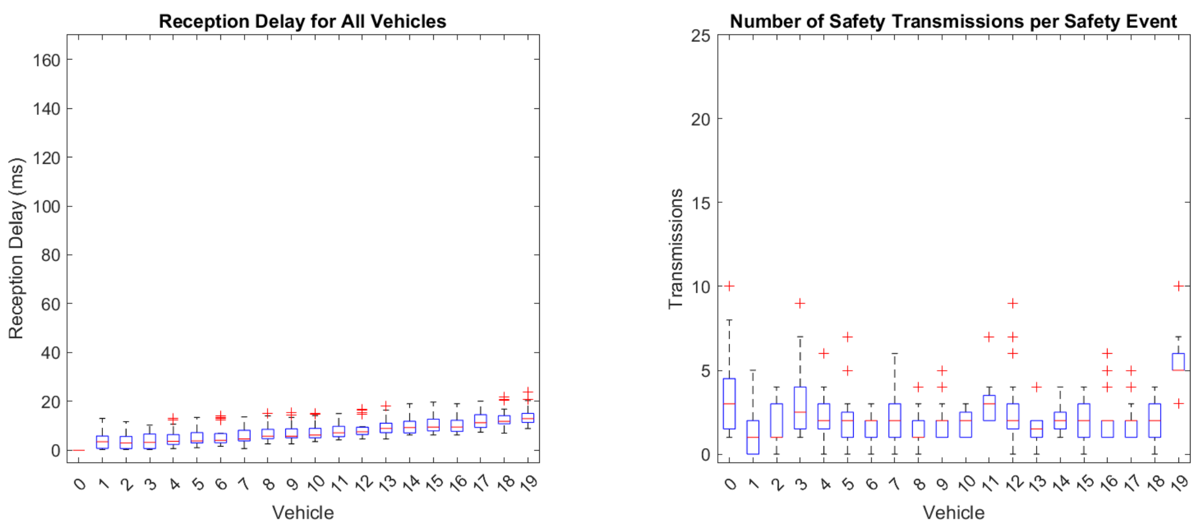

Figure 1. Standard spacing, standard delays. (**Left**): SM reception delay for every vehicle. (**Right**): Number of SM transmissions for every vehicle.

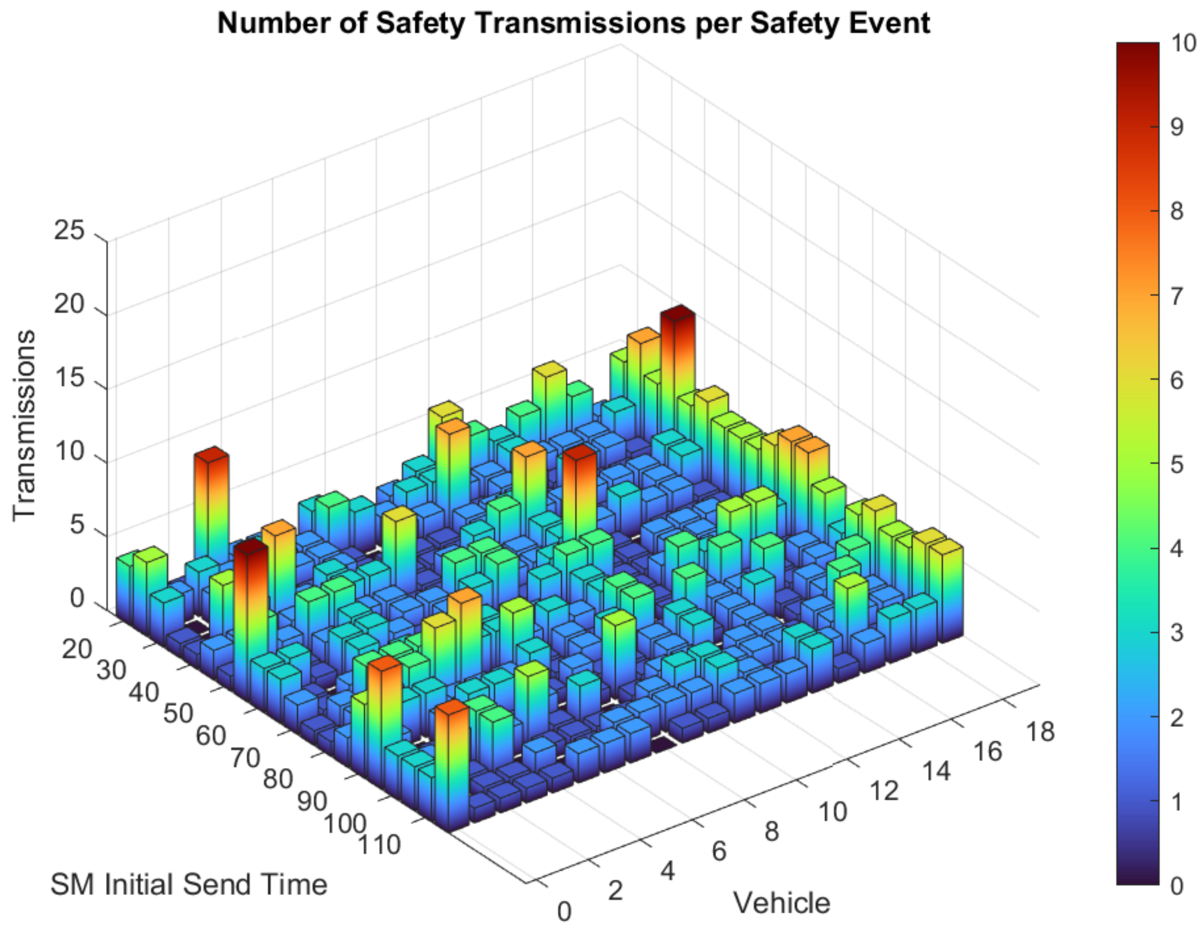

Figure 2. Standard spacing, standard delays. Number of SM transmissions per event for every vehicle given the SM transmission time.

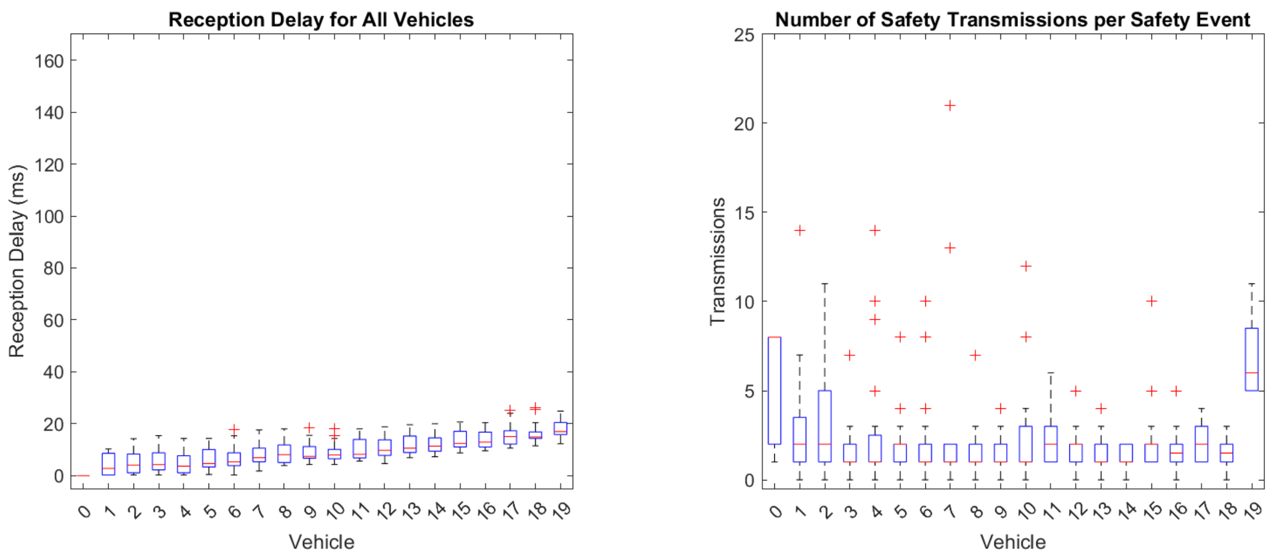

Figure 3. Standard spacing, doubled delays. (**Left**): SM reception delay for every vehicle. (**Right**): Number of SM transmissions for every vehicle.

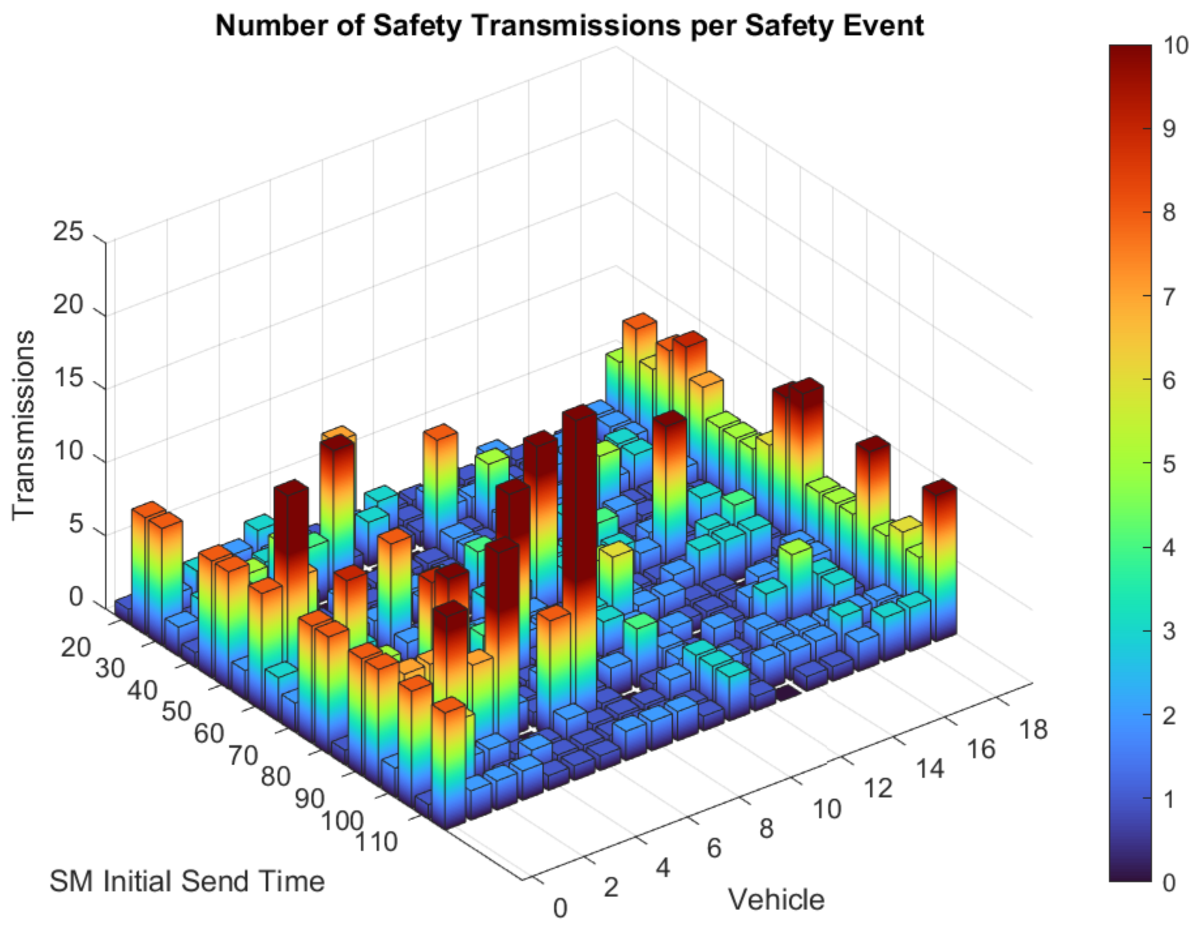

Figure 4. Standard spacing, doubled delays. Number of SM transmissions per event for every vehicle given the SM transmission time.

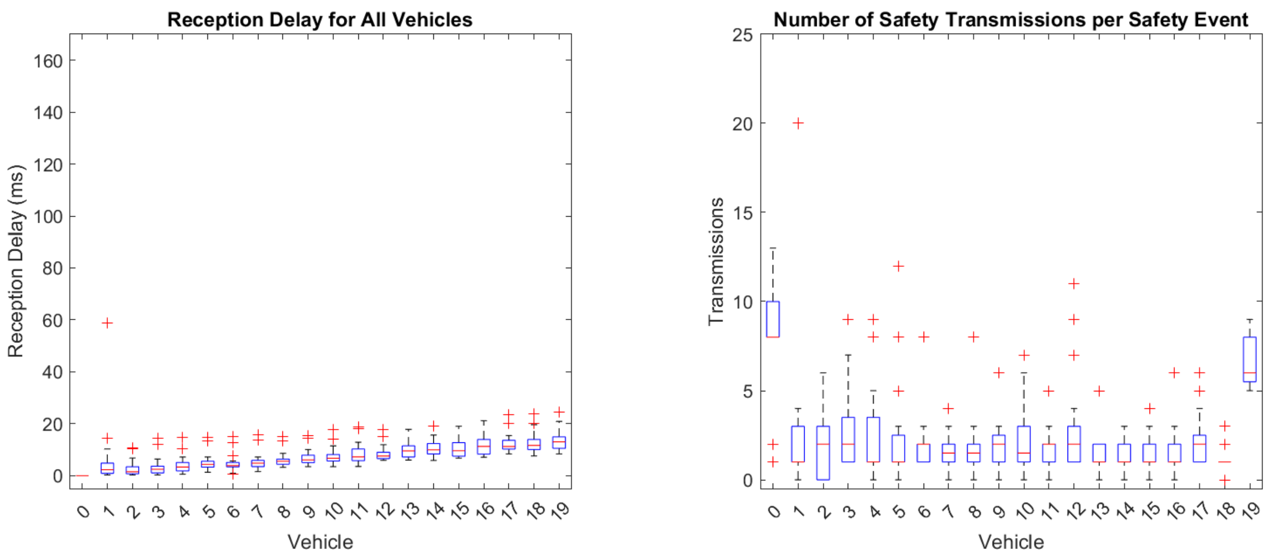

Figure 5. Standard spacing, doubled delay randomness. (**Left**): SM reception delay for every vehicle. (**Right**): Number of SM transmissions for every vehicle.

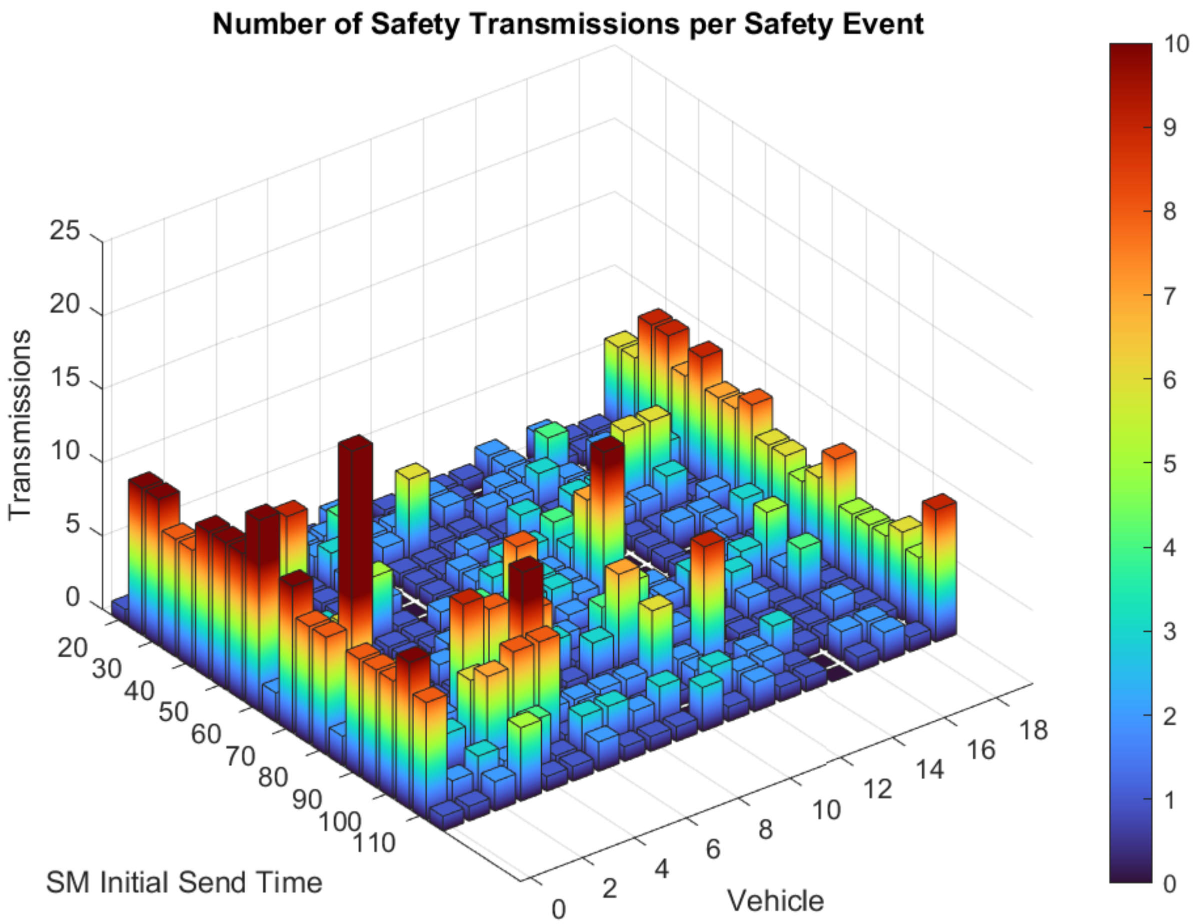

Figure 6. Standard spacing, doubled delay randomness. Number of SM transmissions per event for every vehicle given the SM transmission time.

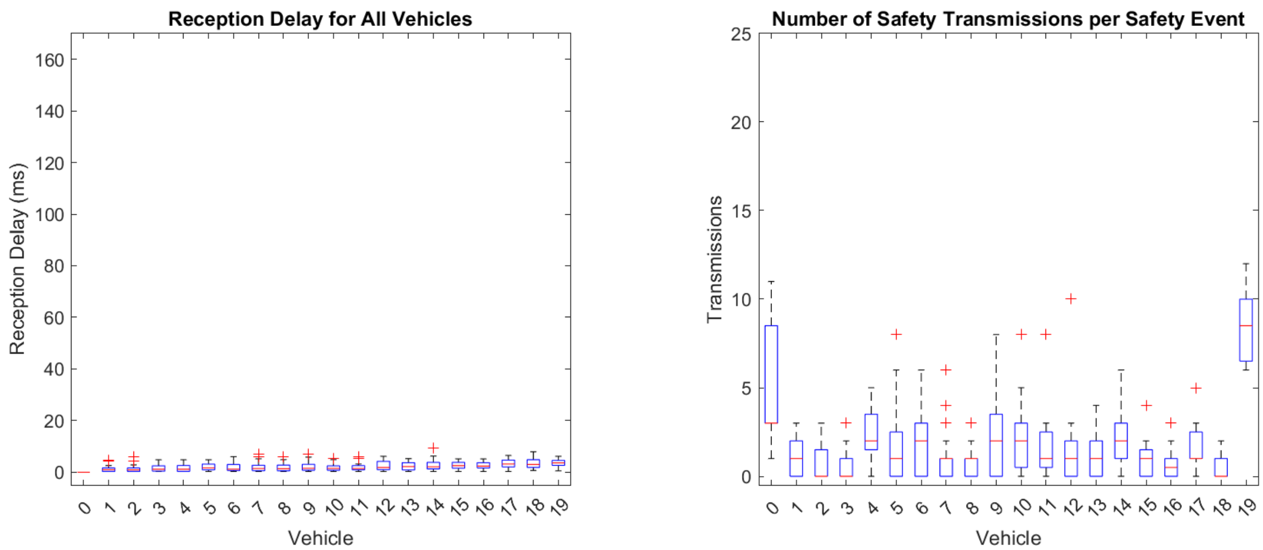

Figure 7. Close spacing, standard delays. (**Left**): SM reception delay for every vehicle. (**Right**): Number of SM transmissions for every vehicle.

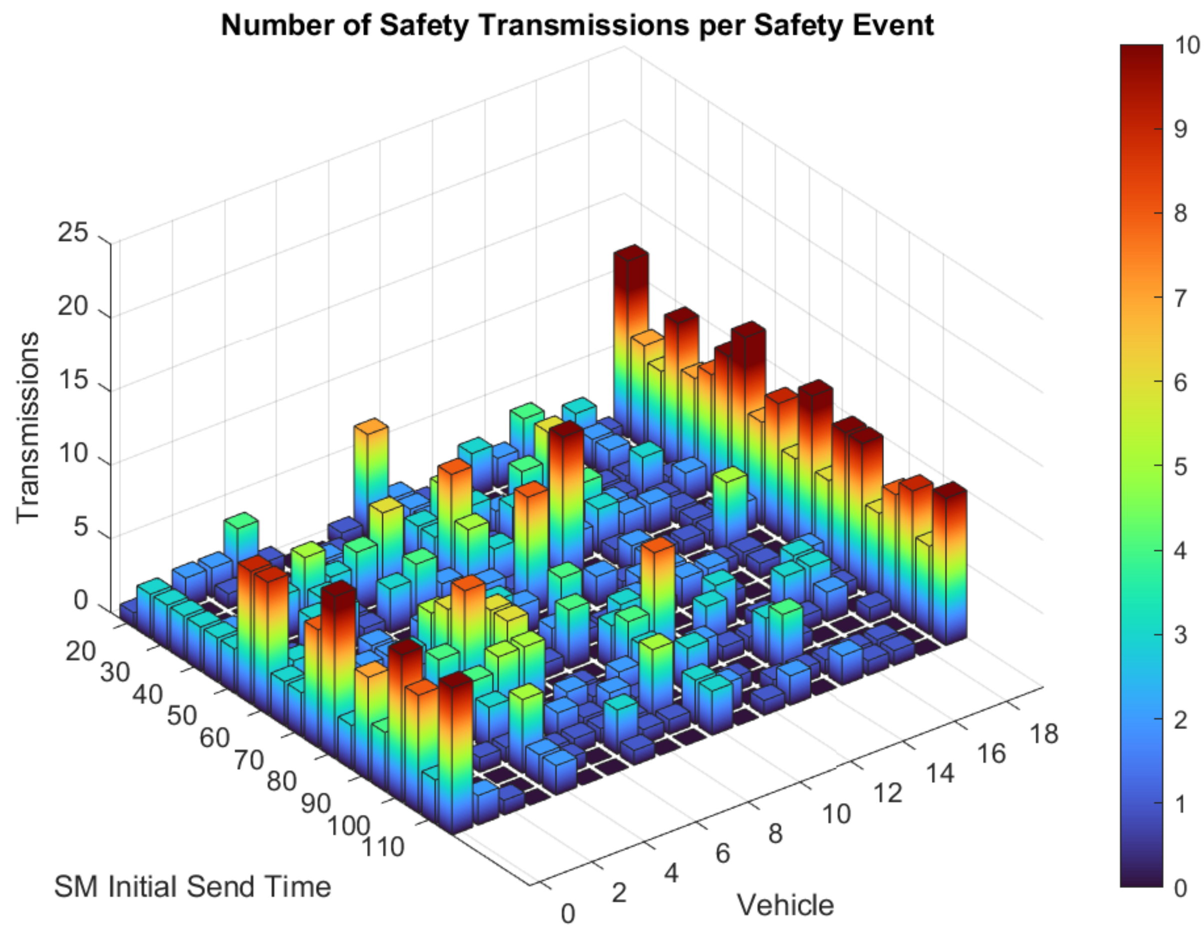

Figure 8. Close spacing, standard delays. Number of SM transmissions per event for every vehicle given the SM transmission time.

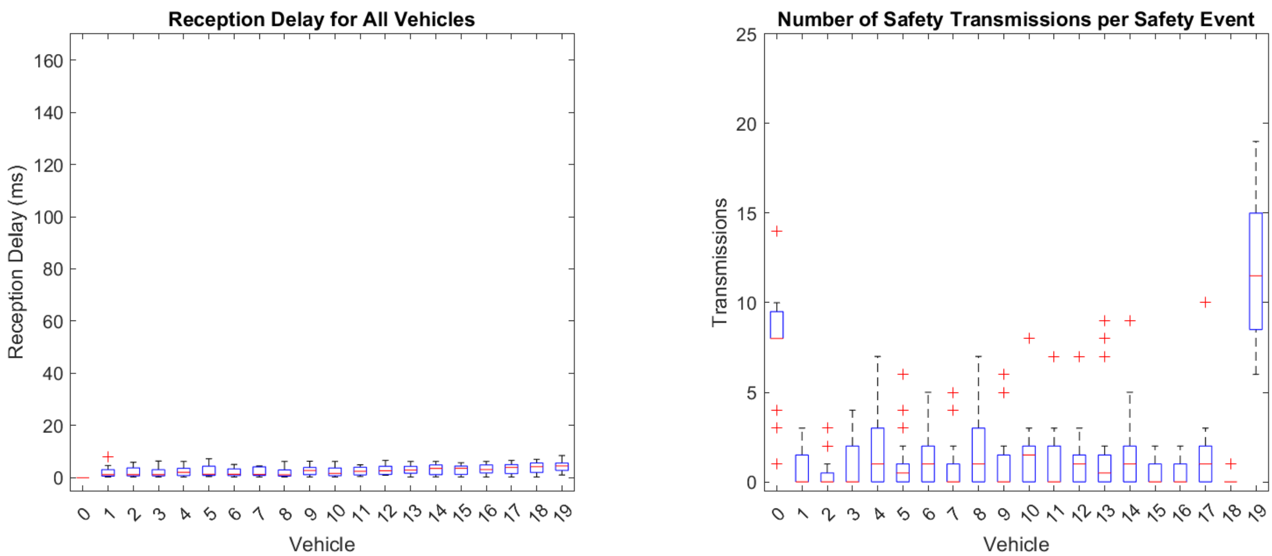

Figure 9. Close spacing, doubled delays. (**Left**): SM reception delay for every vehicle. (**Right**): Number of SM transmissions for every vehicle.

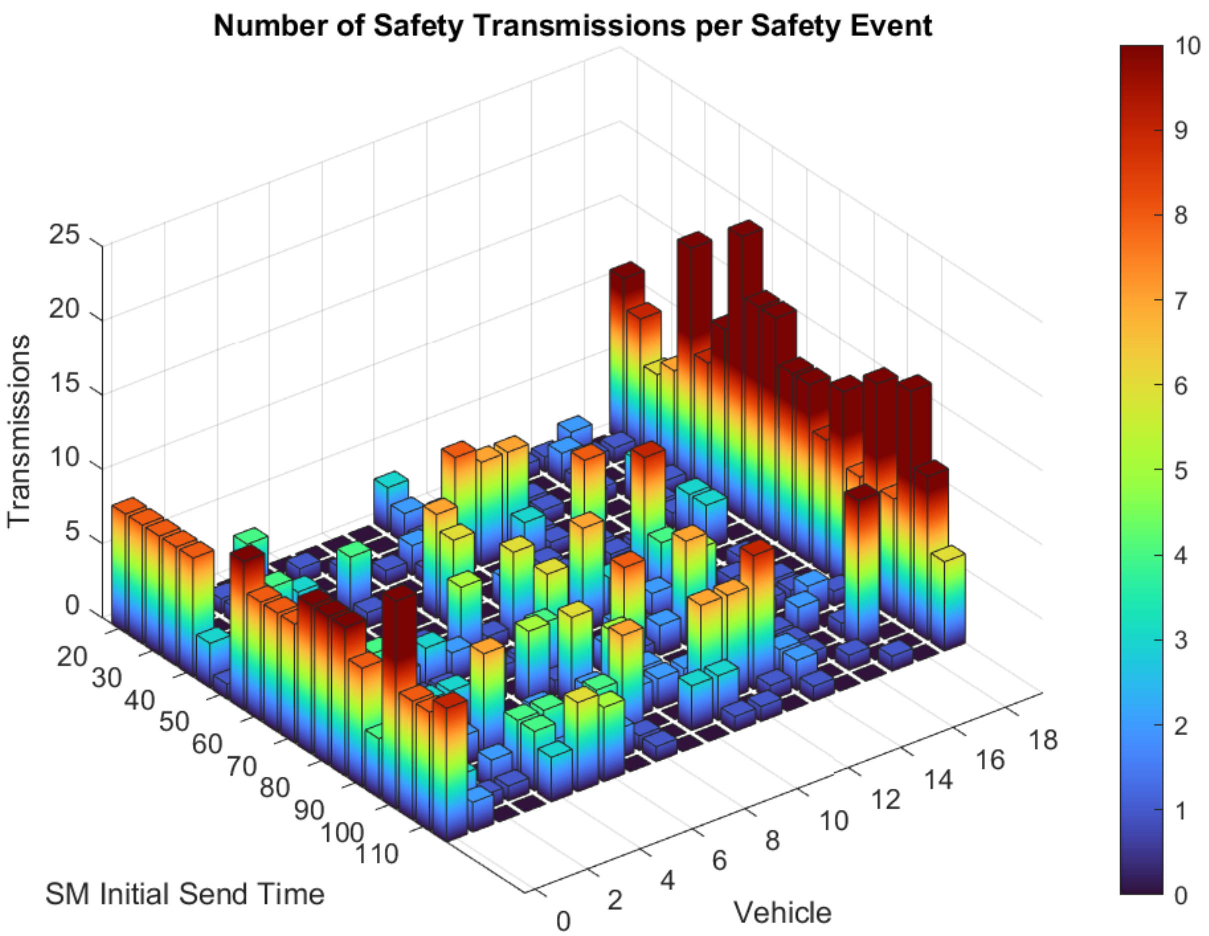

Figure 10. Close spacing, doubled delays. Number of SM transmissions per event for every vehicle given the SM transmission time.

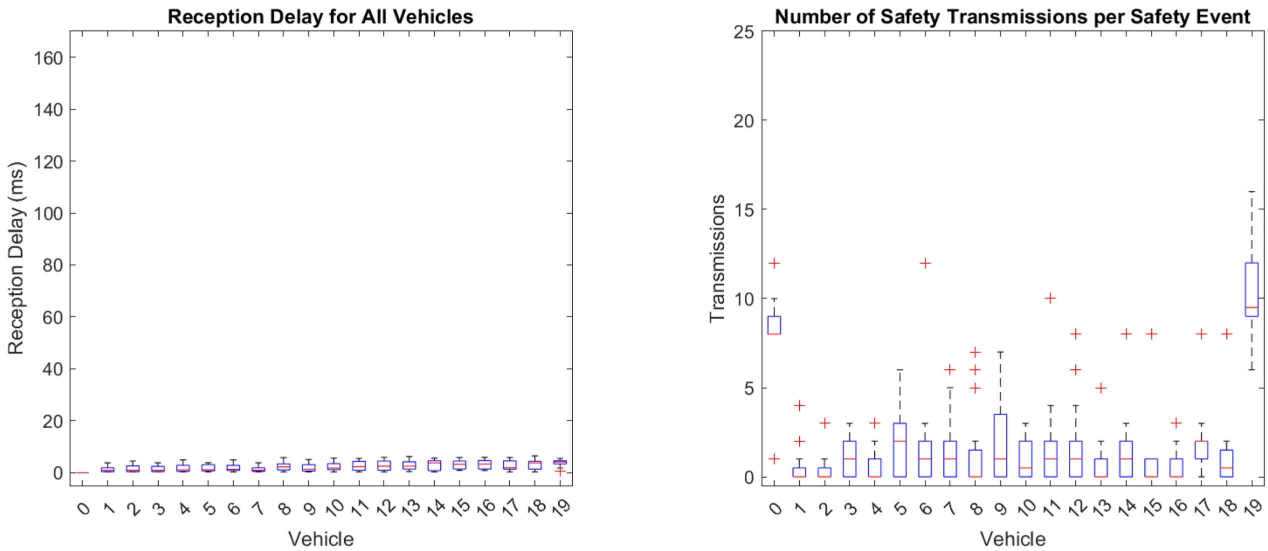

Figure 11. Close spacing, doubled delay randomness. (**Left**): SM reception delay for every vehicle. (**Right**): Number of SM transmissions for every vehicle.

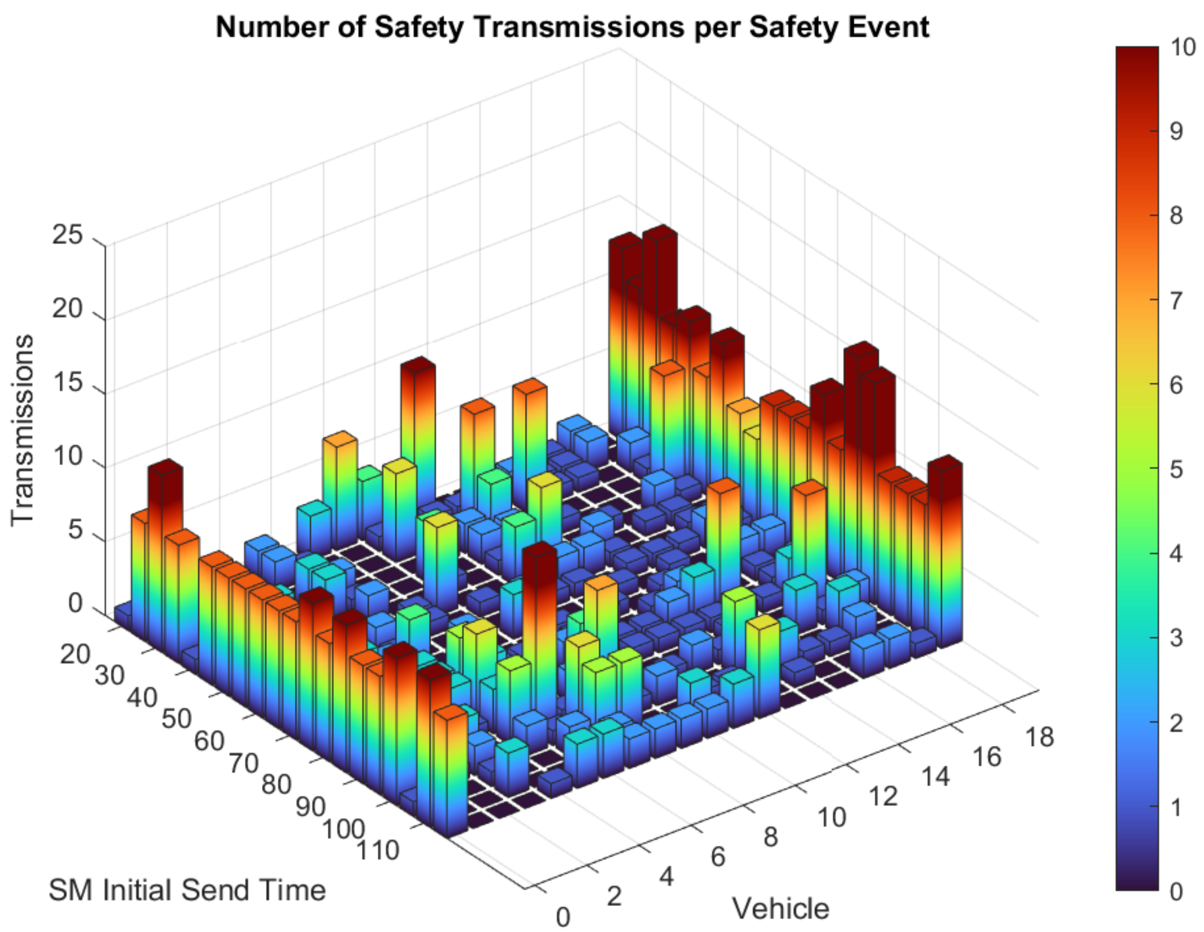

Figure 12. Close spacing, doubled delay randomness. Number of SM transmissions per event for every vehicle given the SM transmission time.

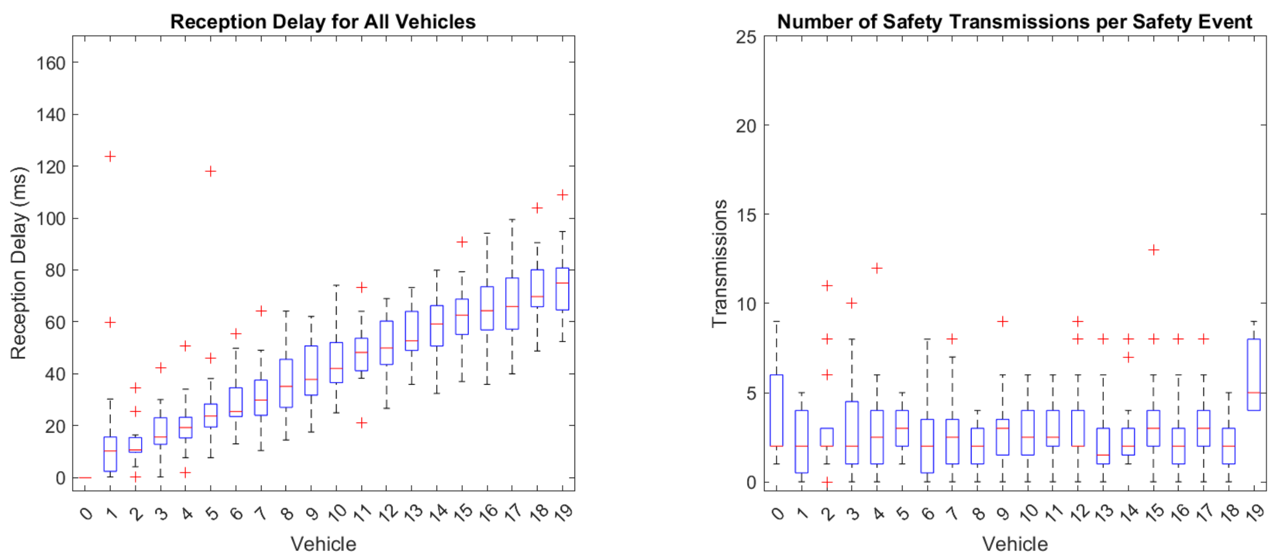

Figure 13. Far spacing, standard delays. (**Left**): SM reception delay for every vehicle. (**Right**): Number of SM transmissions for every vehicle.

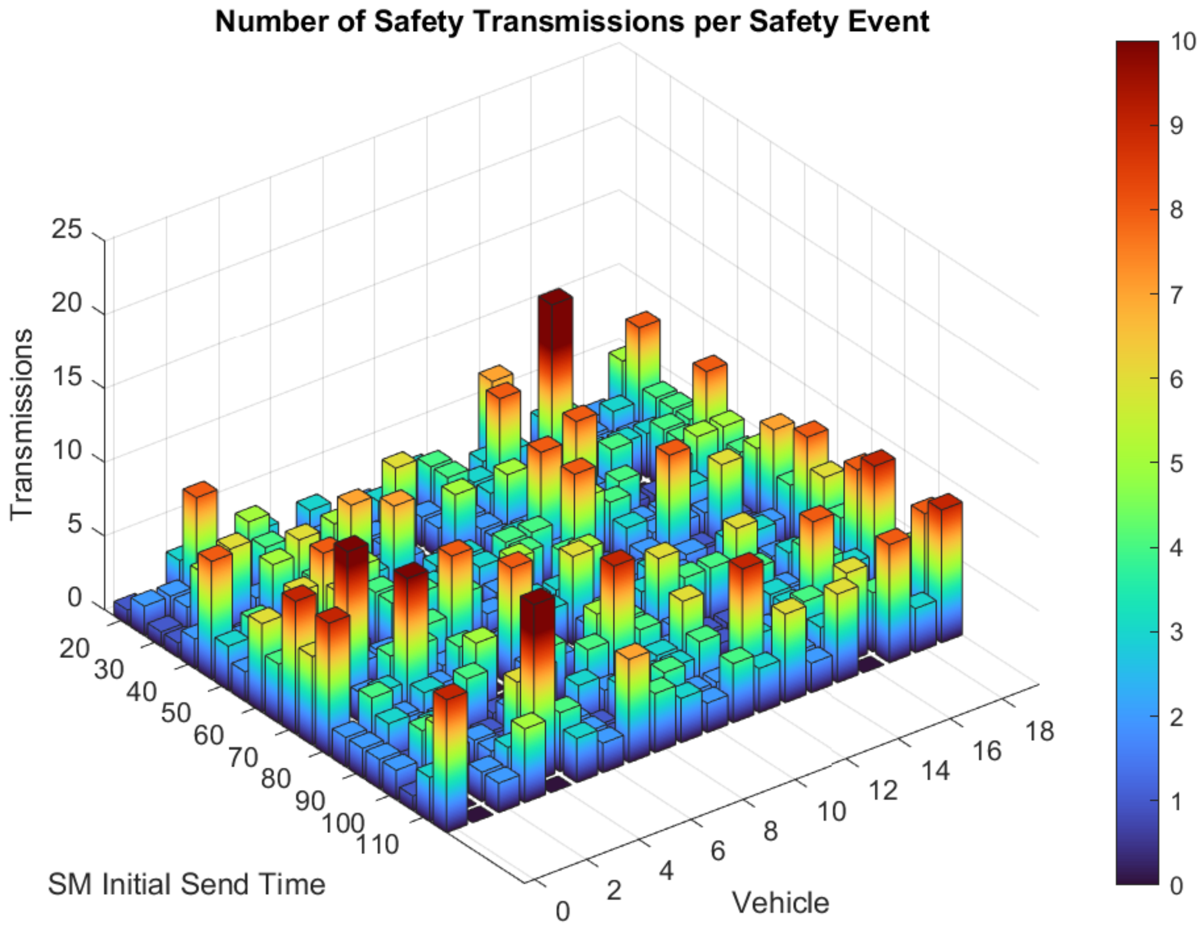

Figure 14. Far spacing, standard delays. Number of SM transmissions per event for every vehicle given the SM transmission time.

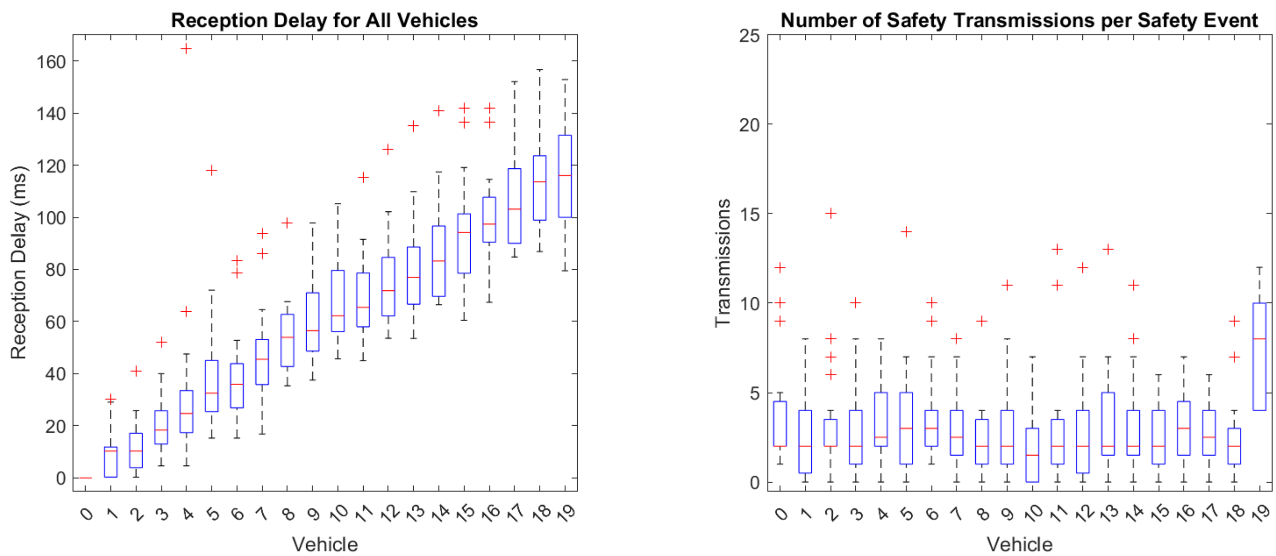

Figure 15. Far spacing, doubled delays. (**Left**): SM reception delay for every vehicle. (**Right**): Number of SM transmissions for every vehicle.

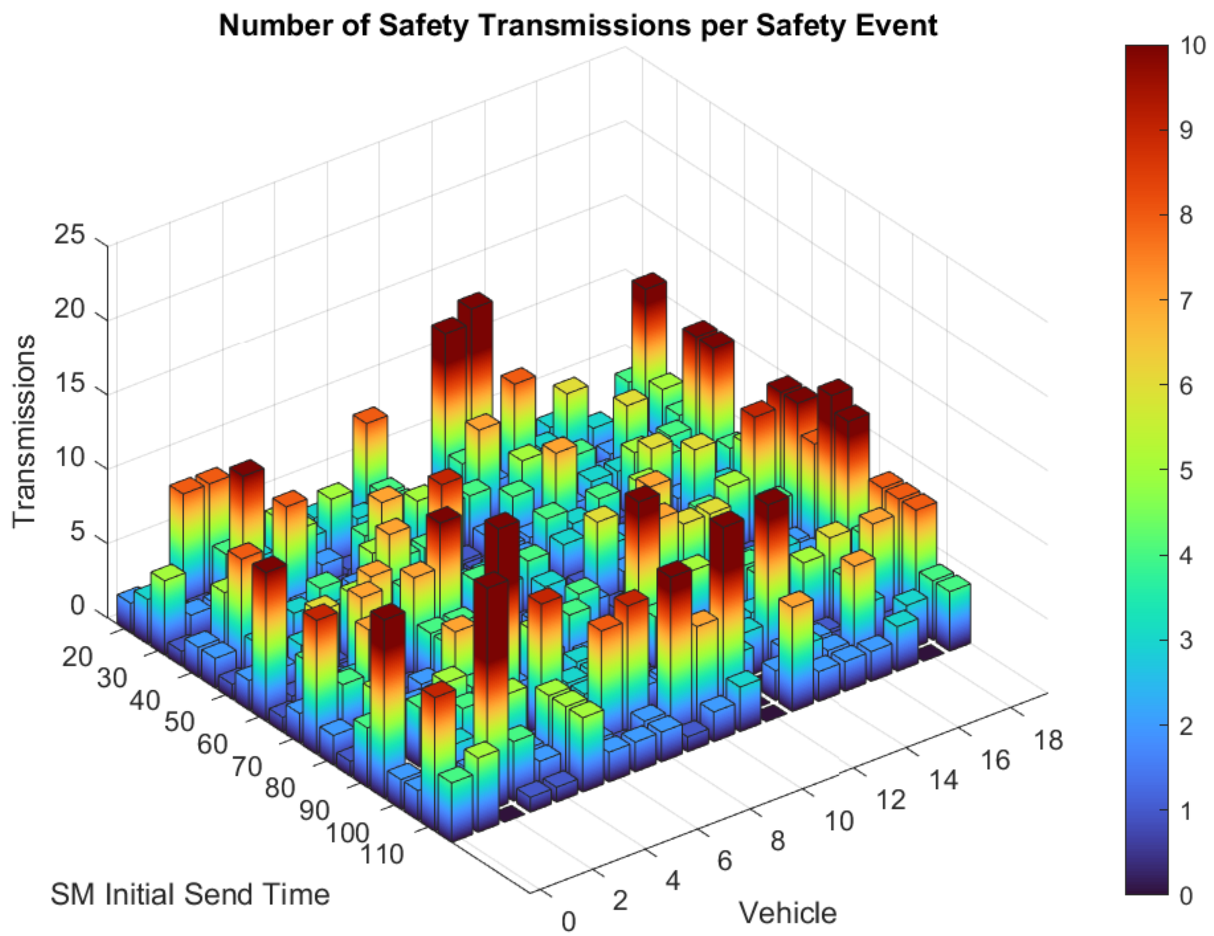

Figure 16. Far spacing, doubled delays. Number of SM transmissions per event for every vehicle given the SM transmission time.

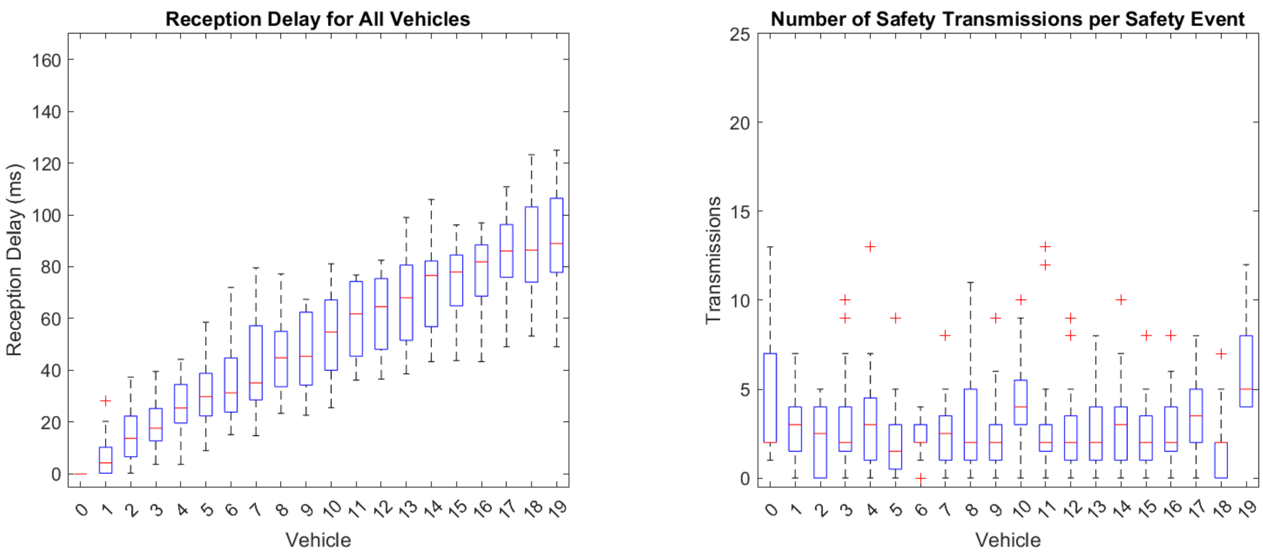

Figure 17. Far spacing, doubled delay randomness. (**Left**): SM reception delay for every vehicle. (**Right**): Number of SM transmissions for every vehicle.

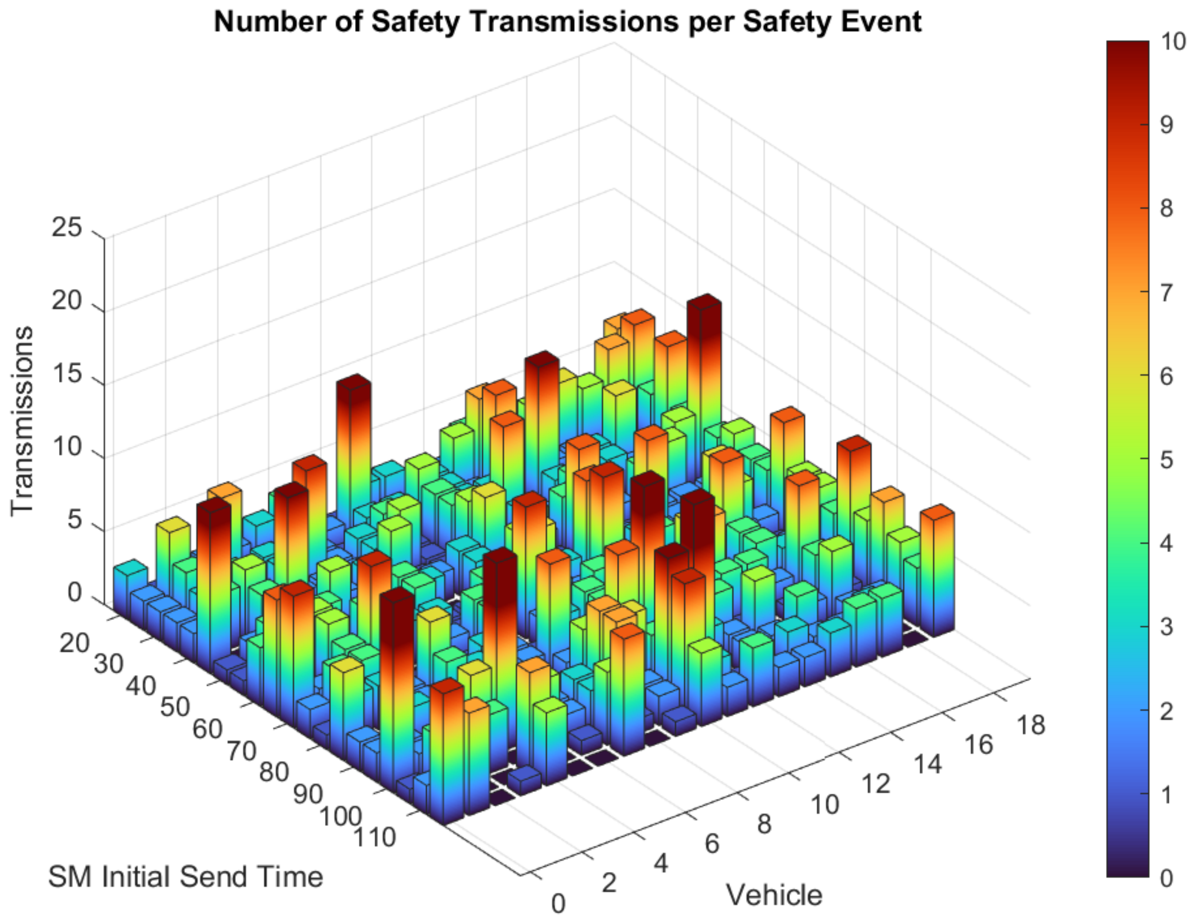

Figure 18. Far spacing, doubled delay randomness. Number of SM transmissions per event for every vehicle given the SM transmission time.

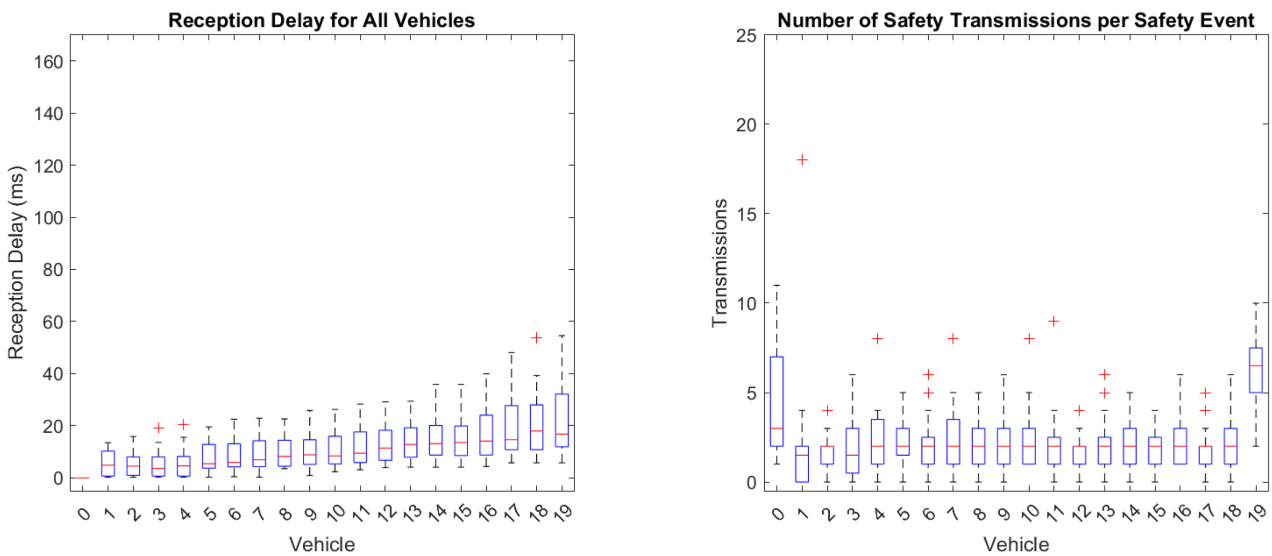

Figure 19. Far-to-close spacing, standard delays. (**Left**): SM reception delay for every vehicle. (**Right**): Number of SM transmissions for every vehicle.

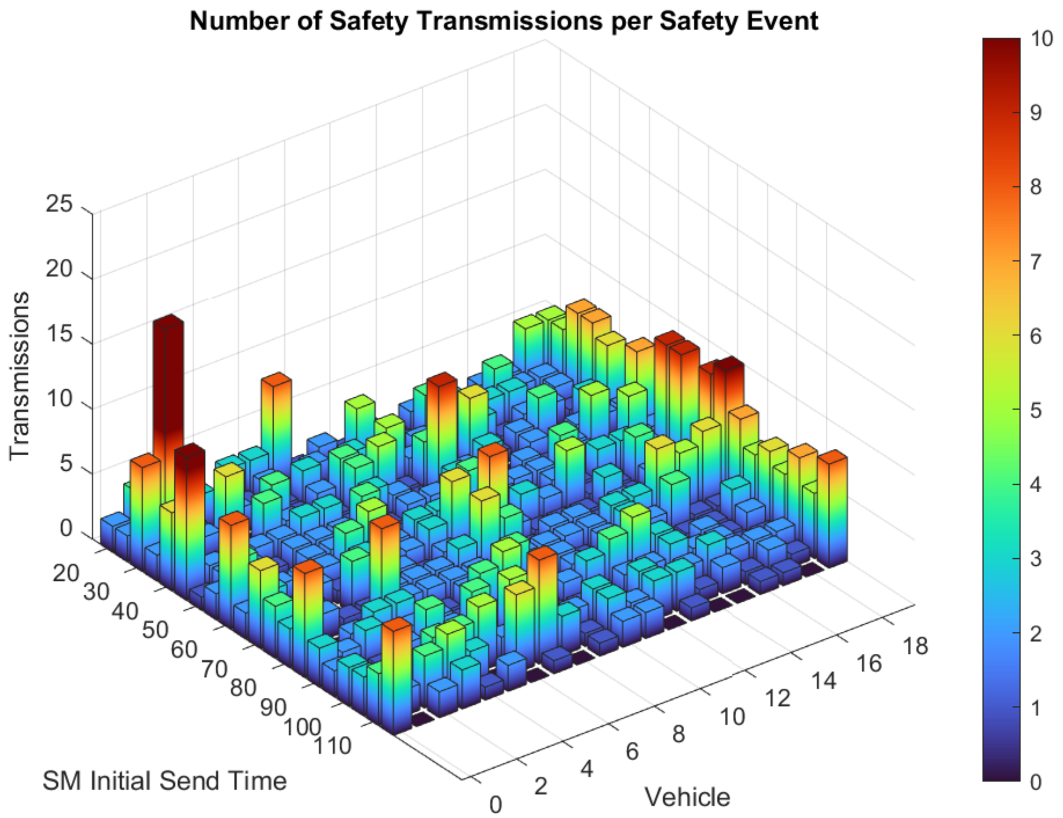

Figure 20. Far-to-close spacing, standard delays. Number of SM transmissions per event for every vehicle given the SM transmission time.

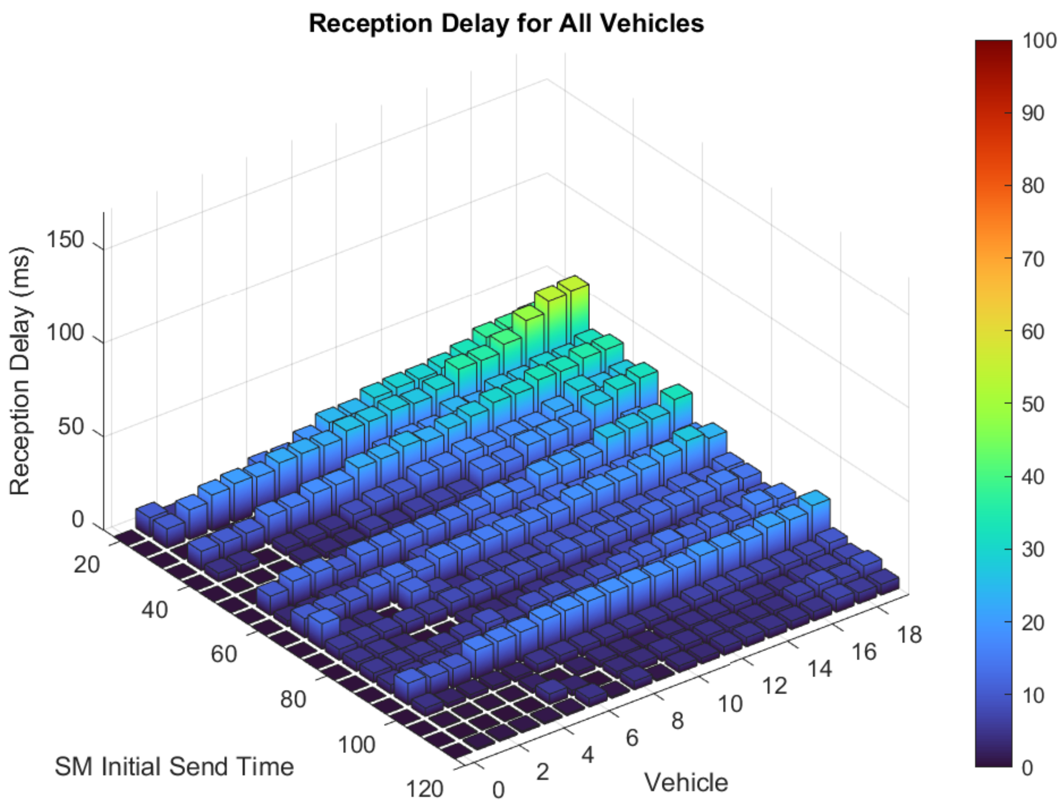

Figure 21. Far-to-close spacing, standard delays. SM reception delay for every vehicle and SM event.

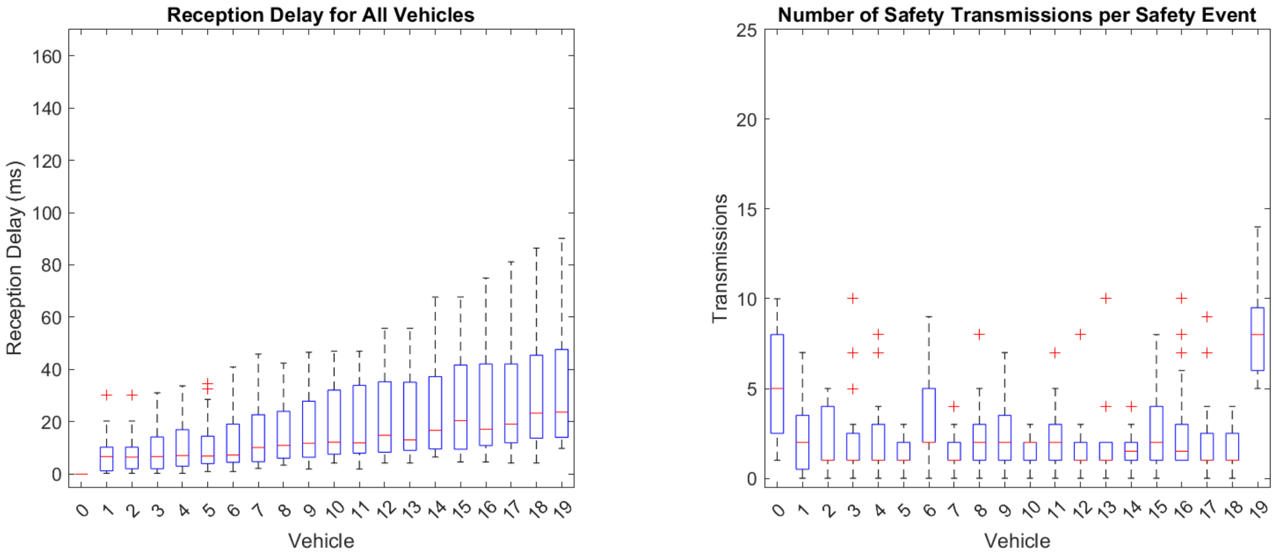

Figure 22. Far-to-close spacing, doubled delays. (**Left**): SM reception delay for every vehicle. (**Right**): Number of SM transmissions for every vehicle.

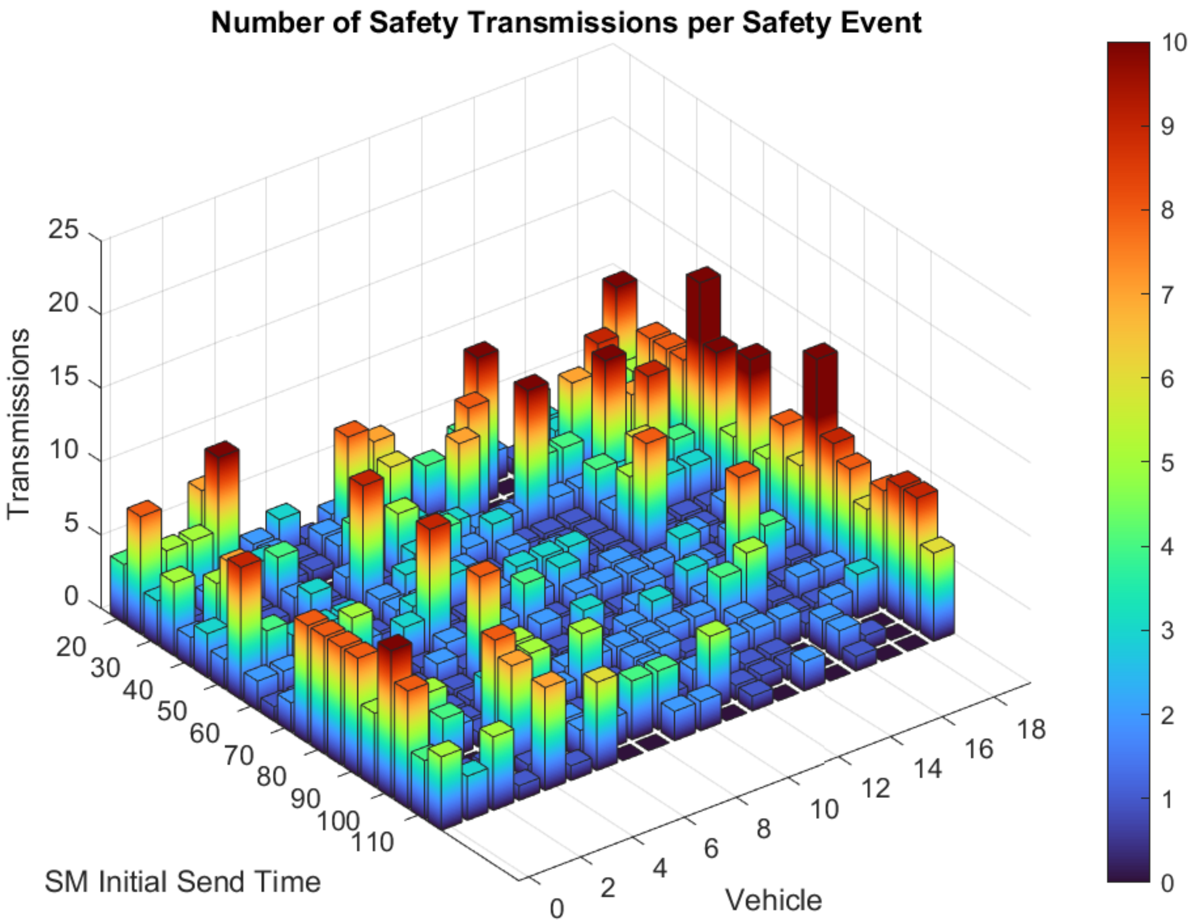

Figure 23. Far-to-close spacing, doubled delays. Number of SM transmissions per event for every vehicle given the SM transmission time.

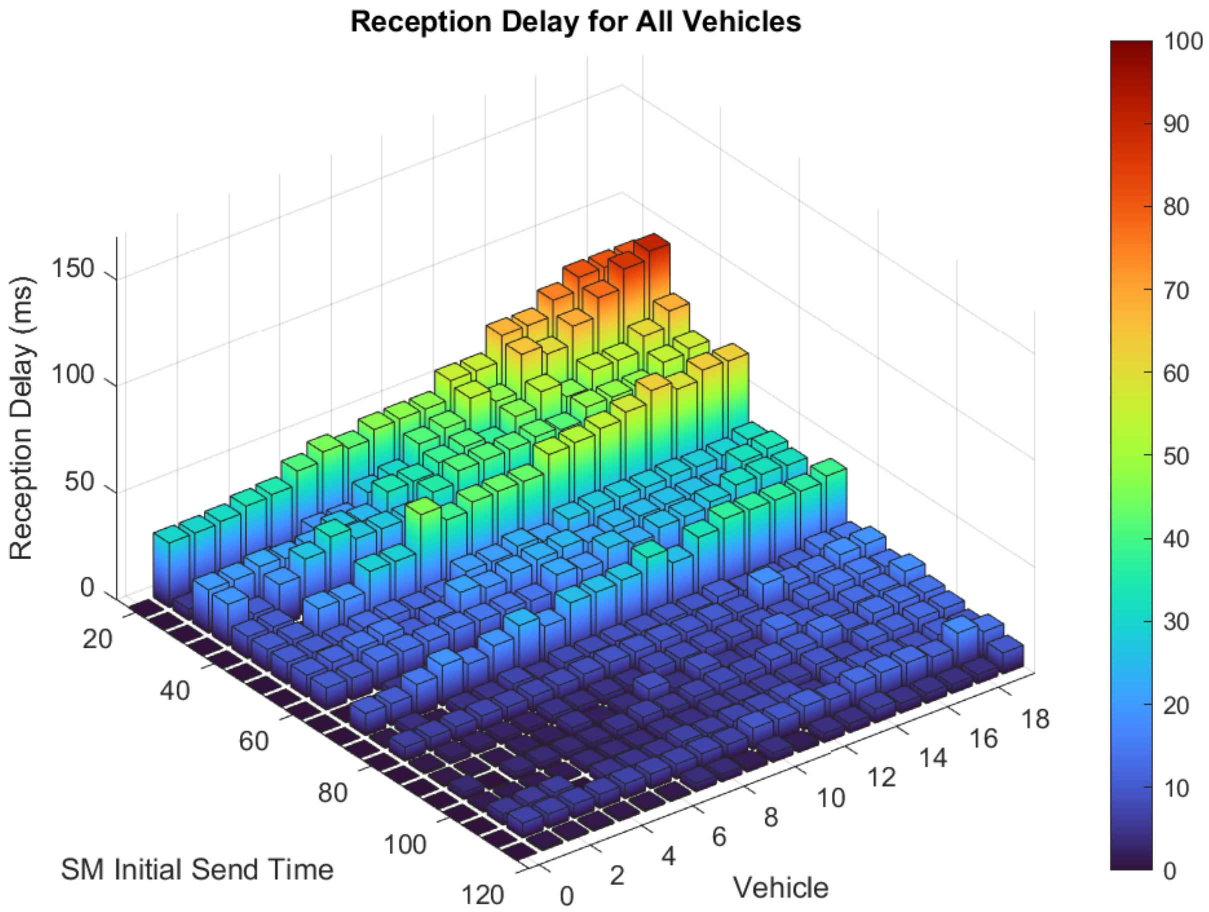

Figure 24. Far-to-close spacing, doubled delays. SM reception delay for every vehicle and SM event.

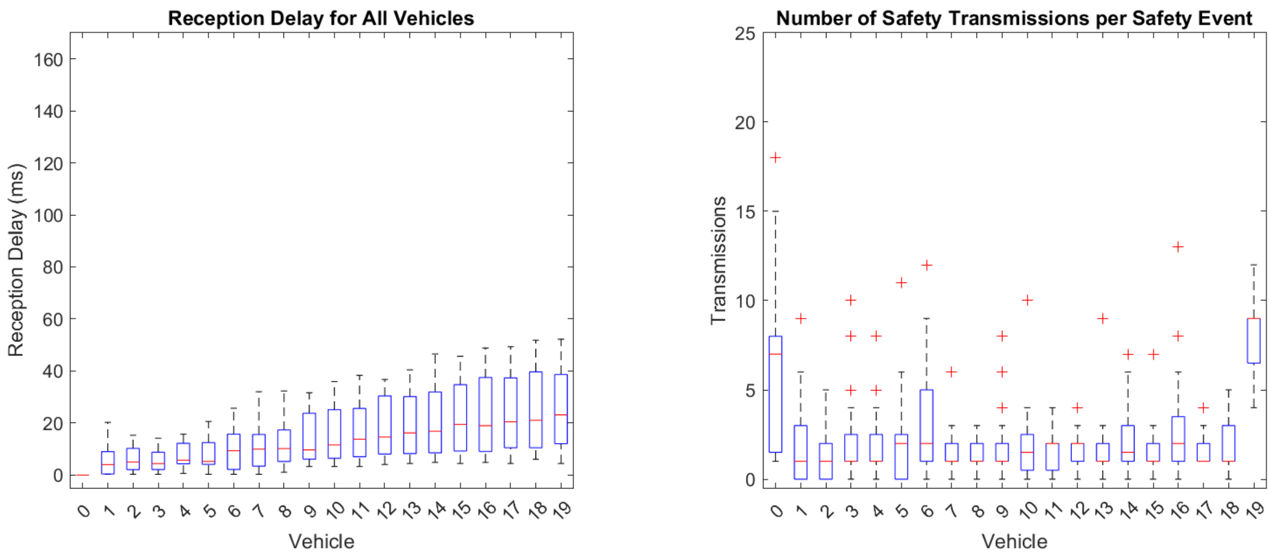

Figure 25. Far-to-close spacing, doubled delay randomness. (**Left**): SM reception delay for every vehicle. (**Right**): Number of SM transmissions for every vehicle.

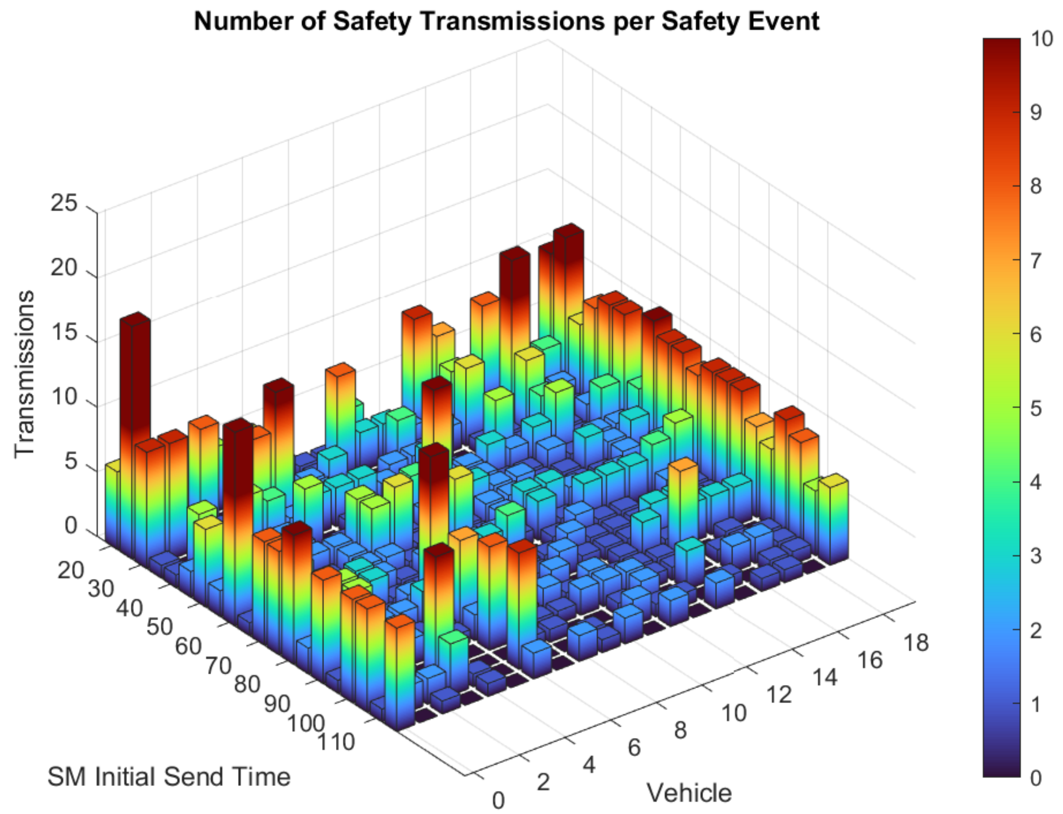

Figure 26. Far-to-close spacing, doubled delay randomness. Number of SM transmissions per event for every vehicle given the SM transmission time.

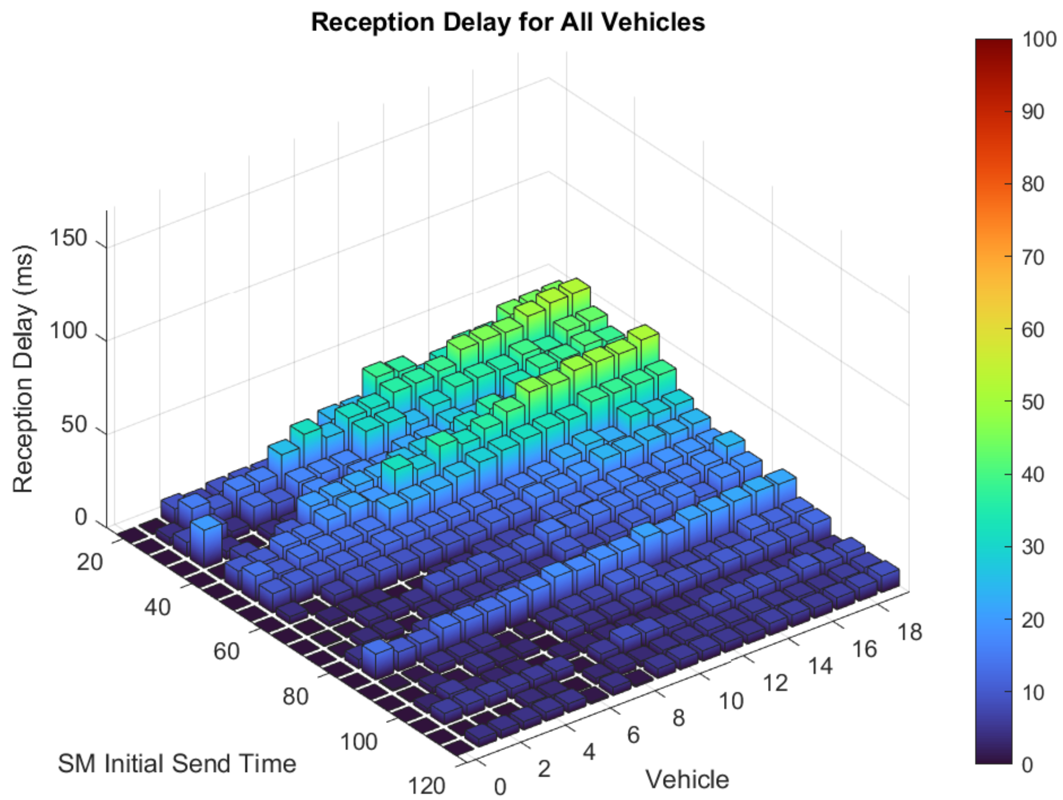

Figure 27. Far-to-close spacing, doubled delay randomness. SM reception delay for every vehicle and SM event.

6. Conclusions

In conclusion, the Convoy VANET system at the very least accomplishes its goal of rapid message propagation in spite of high message loss rates. The key takeaway is that the ability to accurately predict the transmission behavior of ones' peers allows for more rapid decision making with respect to retransmissions. Reducing the unknown variables and their range of values reduces the uncertainty in peer behavior (e.g., the retransmission delay is largely determined by relative position). This, in turn, enables more accurate, implicit knowledge of peers' states and thus smaller delays between necessary retransmissions and faster message propagation. While the channel efficiency aspect likely has room for improvement, the results are reasonably close to intuitive expectations given the channel reliability.

7. Future Work

While the Convoy VANET system works reasonably well in simulation, there are some areas for improvement.

First is the assumption of symmetric channel reliability. This assumption does not hold for many wireless environments. Including wireless reliability metrics for every peer vehicle in the VS may be infeasible at larger scales. However, finding correlations between transmission and reception reliability may allow for a reasonably accurate lower bound to be assumed.

Second is the use of physical distance to scale SM retransmission delays. While this is an unambiguous metric, it suffers from differing behaviors based on convoy length, reception distance, etc. It may be beneficial to utilize the position in the convoy instead. For example, if the PRTX is node X and we are node X-2, then the retransmission delay would be scaled off of the difference in those values (i.e., 2) instead of the physical distance.

Third, making the last vehicle recognize that it is the end of the convoy should be relatively easy to implement. However, outside of simulation, there may be situations where this is not as clear cut and straightforward. For example, the situation becomes more complex if a convoy has a non-convoy vehicle tagging along on the end with a close following distance. If the Convoy VANET is applied to a general use case, then there would need to be a threshold distance at which a trailing vehicle is not considered part of the convoy.

Lastly, the use of uncancelable delayed transmissions should be addressed. This was a stopgap measure implemented to ensure that at least some retransmissions would occur when a node is missing an SM. It was initially assumed that the main retransmission behavior would be concluded before the VS messages would create uncancelable retransmissions. However, given that VS messages can occur at any time, then this system just creates unnecessary channel congestion. Because this is what ensures the eventual reception of every SM, great care must be taken in crafting a solution. The solution must achieve eventual reception while simultaneously allowing for transmissions to be canceled. If SM transmissions had a special tag for this situation, then the system could be modified such that only the target node's messages could cancel the remaining retransmissions. While not receiving a timely response would lead to the same issue, it should at least occur less frequently. Perhaps the channel reliability could be used, where transmissions are only allowed by nodes with a high chance of being heard and a high chance of hearing a response. This may lead to increased delays, as it is reducing the total number of possible transmitters and thus the total number of chances to be heard. Ultimately, this issue must be rigorously tested to ensure it is acceptably fast and reliable.

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Abbreviations

The following abbreviations are used in this manuscript:

ITS	Intelligent Transportation System;
SAE	Society of Automotive Engineers;
V2V	Vehicle-to-Vehicle;
BSM	Basic Safety Message;
VANET	Vehicular Ad Hoc Network;
SM	Safety Message;
PRTX	Preferred Retransmitter;
VS	Vehicle State;
ns3	Network Simulator 3.

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