SAFETY ASSESSMENT OF COOPERATIVE ADAPTIVE CRUISE CONTROL IN AN EMERGENCY BRAKING SCENARIO

A Thesis

by

SHAOJIE YAN

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Chair of Committee,	Swaroop Darbha
Committee Members,	Sivakumar Rathinam
	Shankar P. Bhattacharyya
Head of Department,	Andreas A. Polycarpou

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ABSTRACT

In this thesis, we first introduce a dynamic model of platoon and control strategies. Then we propose a model simulating behaviors of platoons in emergency braking scenario. Time headway and brake capacity follow corresponding distributions in this model. Based on the dynamic model, control strategies and simulation model, we analysis impacts of different parameters, including size of platoon, initial velocity, parasitic latency, packet dropping rate, length of vehicle and control gains k_p and k_v, on the safety of CACC system with respect to probability of collision, expected number of impacts per collision, expected relative velocity at impact and variance of spacing error. In the last part of simulation, we also give some safety sets of gains such that corresponding safety can be promised when gains are in these sets.

Through experiments, We find that initial velocity, parasitic latency, packet dropping rate and gains are eligible to make significant difference on safety of CACC. And size of platoon can only affect severity of collision. Length of vehicle doesn't effect safety at all. In addition, CACC always improves safety in emergency braking scenario over ACC with any parameters.

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NOMENCLATURE

CACC	Cooperative Adaptive Cruise Control
ACC	Adaptive Cruise Control
V2V	Vehicle-to-vehicle
k_p	Position Gain
k_v	Velocity Gain
k_a	Acceleration Gain
h_w	Time Headway
v	Initial velocity
τ	Parasitic Latency
t	Time Step
L_o	Length of Vehicle
D_i	Maximum Deceleration of i^{th} Vehicle
S	Default Set of Parameters
s	Size of platoon

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1. INTRODUCTION AND LITERATURE REVIEW

Cooperative Adaptive Cruise Control (CACC) system is still one of the most popular topics in the area of Intelligent Transportation Systems (ITS). CACC systems serve as Advanced Driver Assist Systems (ADAS) and can potentially help enhance the current transportation system in terms of safety, mobility and sustainability. Researchers mention that driving safety and road capacity will be increased while energy consumption and pollutant emissions will be decreased by taking advantages of CACC[1].

In a CACC system, a host vehicle receives the acceleration information from its predecessor in the lane and communicates its acceleration information with its following vehicle. In CACC+ systems, a host vehicle communicates its information with other vehicles in the string by vehicle-to-vehicle (V2V) communications. [2].

Two central issues concerning CACC are string stability and safety - the former issue has received significant attention in literature. Darbha et al. proved V2V communication can reduce the minimum employable time headway in terms of string stability and provided an analytical bound [3]. Based on this work, Vegamoor et. al. generalized the relationship between minimum employable time headway to maintain string stability and communication packet drops [4].

Improvement of safety is another potential benefit of CACC system. CACC system can potentially enable vehicles to safely maintain smaller time headway than vehicles equipped with Adaptive Cruise Control (ACC) system if all vehicles have the same initial following distance and velocity and identical braking capability for vehicles in the string (or platoon) [5]. For the situation where vehicles have different maximum deceleration, coordination among vehicles can improve safety as well[6]. Rafaelet al. discuss the safety of CACC under unreliable inter-vehicle communications[7]. Lian et al. develop a simulation platform for safety analysis considering communication lags, sensor errors and vehicle dynamics[8].

There has been some research on the assessment of safety of CACC system under different scenarios with various conditions, but there is a significant gap in research showing the impacts of parameters on the enhancements of safety provided by CACC Systems in a systematic way. No work in the literature focuses on how much the gains of control strategy will affect the safety of vehicle platoon equipped with CACC Systems. Past works have dealt with assessment of safety enhancement provided by CACC under unreliable communications[7], and with a deceleration distribution among vehicles in the platoon[6] separately. However, when CACC systems are deployed, one must consider all of them jointly - distribution of braking capability of vehicles, actuation latencies, packet drops etc. and then address the question: despite all these shortcomingss, will CACC still behave better or at least same as ACC does? Based on a simulation model, we show that the safety improvement provided by CACC systems by considering variance of time headway and deceleration capacity, packet dropouts and parasitic latencies. In this thesis, we analyze the impact of different parameters on the safety of CACC system as well as numerically corroborate the safety improvements that are possible with a CACC system when compared with an ACC system.

There are several ways to metrize safety. Ye et al. evaluate the impacts of CACC on reducing collision risks measured by time-to-collision (TTC), time exposed time-to-collision (TET) and time integrated time-to-collision (TIT)[9]. We use the criteria based on the one introduced in [6] to assess safety as following. We assume strategy A is better than strategy B in terms of safety, if the collision probability, expected number of collisions and expected velocity at impact under strategy A is lower than those three values under strategy B. Besides that, we also assume that strategy A is better than strategy B, if the variance of spacing error of a certain vehicle controlled by strategy A is less than the variance of spacing error of the same vehicle controller by strategy B.

There are many scenarios of CACC that people working on. Qing et al. contribute to simulation, analysis and compare ACC and CACC in highway merging scenario[10]. Yu et al. evaluate longitudinal safety impacts of CACC degradation[11]. We assess the safety of CACC system in the emergency braking scenario, since rear-end collision is the most usual type of collisions and most of rear-end collisions result from stopping of the leading vehicle.

2. PROBLEM DESCRIPTION AND SIMULATION SETTING

2.1 Dynamic Model of Platoon

Consider a platoon of n vehicles as shown below:

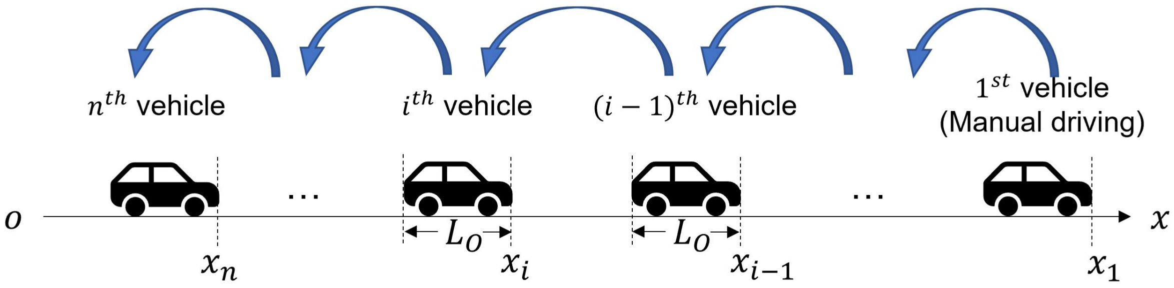

Figure 2.1: Schematic of a n-vehicle platoon

The vehicle platoon moves to right in a straight line with the first vehicle being the leading vehicle. The leading vehicle of platoon is manually driven with $n-1$ following vehicles equipped with CACC systems. In emergency braking scenario, the leading vehicle brakes as much as it can and the following vehicles brake according the corresponding control strategy. For simplicity, drag terms are neglected and so is the effect of restitution in a collision.

Each vehicle in the platoon is regarded as a point mass with a rigid massless extension equivalent to a car length, L_0. Without loss of generality, we consider its position as the position of the leading point of the rigid extension. We assume that acceleration is controlled by a first order actuation dynamics:

$$\ddot{x}_i = a_i, \quad \tau \dot{a}_i + a_i = u_i \tag{2.1}$$

where x_i is the position of i^{th} vehicle in platoon, a_i and u_i is the acceleration and control input of i^{th} vehicle respectively. And τ is the *maximum* parasitic actuation latency of vehicles in the platoon. For the purposes of implementation, $\tau = 0$ (i.e., actuation dynamics is ignored); this model has been used successfully in California PATH projects[12]. However, from the robustness viewpoint, one must consider parasitic lags in actuation and sensing; this is what we adopt here. More discussion on the choice of this model is provided in [13].

The control strategy of CACC is given as following:

$$u_i(t) = \begin{cases} -D_1 & \text{if } i = 1 \\ \max\{-k_p(x_i - x_{i-1} + h_{wi}\dot{x}_i + L_0) - k_v(\dot{x}_i - \dot{x}_{i-1}) + k_a\ddot{x}_{i-1}, -D_i\} & \text{otherwise} \end{cases} \tag{2.2}$$

where D_1 and D_i represent deceleration capacity (maximum deceleration) of the first and i^{th} vehicle respectively. h_{wi} is the i^{th} vehicle's time headway, L_0 is the length of a vehicle, which is assumed to be the same for every vehicle in the platoon. k_p, k_v, k_a are gains of controller. The acceleration gain k_a must lie between 0 and 1 to maintain string stability[14]; when k_a reduces to 0, the control strategy reduces to ACC strategy:

$$u_i(t) = \begin{cases} -D_1 & \text{if } i = 1 \\ \max\{-k_p(x_i - x_{i-1} + h_{wi}\dot{x}_i + L_0) - k_v(\dot{x}_i - \dot{x}_{i-1}), -D_i\} & \text{otherwise} \end{cases} \tag{2.3}$$

2.2 Simulation Settings

2.2.1 Discrete Model

For the sake of simulation, we assume in a small enough time interval Δt, u_i and a_i are unchanged for every i in platoon. This is reasonable because of digital implementation of control laws, where the control input is held constant for the duration of the control sample time. We discretize the vehicle dynamic model in equation 2.1 to obtain:

$$x_i(t+\Delta t) = \dot{x}_i(t)\Delta t + x_i(t) + \frac{1}{2}a_i(t)(\Delta t)^2 \tag{2.4}$$

$$\dot{x}_i(t+\Delta t) = \dot{x}_i(t) + a_i(t)\Delta t \tag{2.5}$$

$$a_i(t+\Delta t) = \frac{1}{\tau}(u_i(t) - a_i(t))\Delta t + a_i(t) \tag{2.6}$$

The CACC control strategy expressed in equation 2.2 simplifies to:

$$u_i(t+\Delta t) = \begin{cases} -D_1 & \text{if } i = 1 \\ \max\{-k_p(x_i(t) - x_{i-1}(t) + h_{wi}\dot{x}_i(t) + L_0) & \\ \qquad -k_v(\dot{x}_i(t) - \dot{x}_{i-1}(t)) + k_a\ddot{x}_{i-1}(t), -D_i\} & \text{otherwise} \end{cases} \tag{2.7}$$

By the same token, ACC control strategy transforms into:

$$u_i(t+\Delta t) = \begin{cases} -D_1 & \text{if } i = 1 \\ \max\{-k_p(x_i(t) - x_{i-1}(t) + h_{wi}\dot{x}_i(t) + L_0) & \\ \qquad -k_v(\dot{x}_i(t) - \dot{x}_{i-1}(t)), -D_i\} & \text{otherwise} \end{cases} \tag{2.8}$$

2.2.2 Collision Check

In this thesis, the safety of CACC is assessed in an emergency braking scenario - the leading vehicle will brake with his maximum deceleration at 0 second and the following vehicles brake in response to the leader according to their respective vehicle following law. This simulation of an emergency braking scenario is setup for 25 seconds, which is sufficient for all vehicles in the platoon to stop completely. We adopt Monte Carlo type approach for assessment of safety; we vary parameters systematically in a chosen range and draw a realization of random variables - for example, the braking capability of vehicles, packet drop etc. Assessment of safety is done as follows: in each realization, we will check whether there is a collision during the emergency braking scenario, count the number of collisions along with the relative velocity at collision between all pairs of vehicles that were involved in the collision.

Here are the assumptions for the simulation and collection of data from each realization:

- When two vehicles overlap, in other words, if $x_i > x_{i-1} - L_o$, we consider that i^{th} vehicle and $(i-1)^{th}$ vehicle collide.

- Since we do not consider the effect of restitution in a collision, if two vehicles collide, we assume that both vehicles stop immediately and can not move anymore for the rest of simulation for that particular realization. However, if one vehicle (except the leading vehicle) stops itself without collision, it can accelerate and only move forward again.

- When we count the number of collisions that happen in one realization, we focus on the collisions instead of the vehicles. For instance, the numbers of collisions are same for the two cases - one where the second vehicle collides with the first vehicle and then the third vehicle collide with the second vehicle and the second case where a collision happens between the first vehicle and the second vehicle and another collision happens between the third vehicle and the fourth vehicle. The number of collisions is 2 in both cases.

2.2.3 Initial Conditions

Since we change several parameters during the thesis, to make the results easier to understand , we propose a default parameter set to compare with. The default set S is $\{\ k_p = 0.8$, $k_v = 2$, $v = 30\ m/sec$, $\tau = 0.4\ sec$, $L_o = 3\ m$, $r = 0.5\ s = 10\}$, where v is the homogeneous initial velocity for all vehicles in the platoon, r is the packet dropping rate, e.g. the following vehicle has a probability of 70% to miss the massage in a time instance when $r = 0.7$, and s is the size of platoon including a leading vehicle with manual driving. Every time we assess the impact of a parameter on the safety of CACC, we keep other parameters with default value as they are in set S.

The braking capability of each vehicle is assigned randomly based on an independent and identical probability distribution given in the paper by Godbole and Lygeros as shown in figure 2.2

(1997)[15].

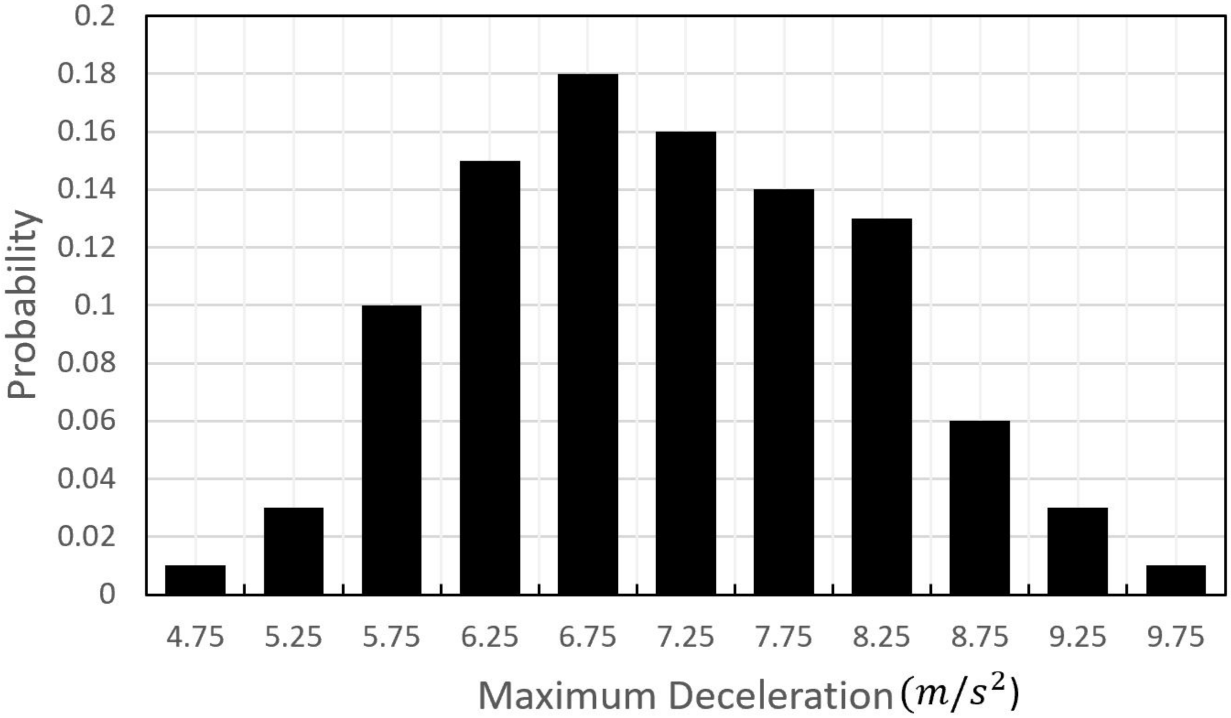

Figure 2.2: Probability Distribution for Maximum Deceleration

The time headway of each vehicle follows a discrete uniform distribution on $0.8sec$, $0.9sec$, $1.0sec$, $1.1sec$ and $1.2sec$. After both initial velocity and time headway are set, the initial position for vehicle in the platoon is:

$$x_i(0) = \begin{cases} 0 & \text{if } i = n \\ x_{i+1}(0) + L_o + h_{wi}v & \text{otherwise} \end{cases} \tag{2.9}$$

So the initial spacing error (defined as $x_i - x_{i-1} + h_{wi}\dot{x}_i + L_o$) is zero, which means vehicles are initially maintaining their respective desired following distances. Initially, the acceleration/deceleration of every vehicle in the platoon is zero.

2.2.4 Simulation Algorithm

With all initial conditions set, simulation with a certain set of parameters are shown in figure 2.3. Nested loops are used in simulations. In the outer loop, time is incremented, while in the inner loop index of vehicle is incremented. Each time we go through the inner loop, we check for collisions first and then look for stopped vehicles. Depending on whether collisions and stops happen, states of vehicles will get updated in different methods. If i^{th} vehicle does not collide with following ($(i+1)^{th}$) vehicle or stop, states of i^{th} vehicle will get updated by corresponding control strategy. If the leading vehicle does not collide with following vehicle but stop, it will remain at same position with zero velocity and zero deceleration. If an unmanned vehicle (with either CACC or ACC system) does not collide with following vehicle but stops, it will restart and move forward controlled by corresponding inputs. The last case considers the case when the i^{th} vehicle collides with its following vehicle, which leads to two vehicles two vehicles stopping immediately in the simulations and stay at the that position for the rest of realization.

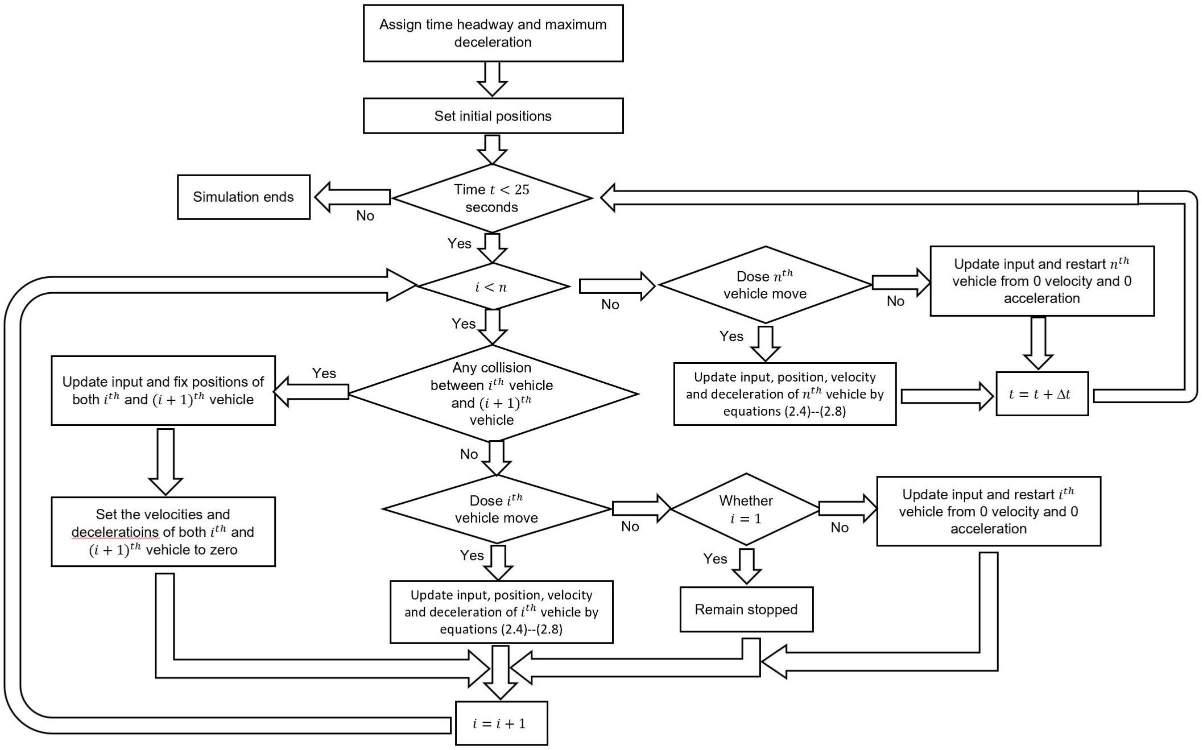

Figure 2.3: Flow Chart of Simulation

Since each vehicle in the platoon is given one of eleven possible values of maximum deceleration and one of five time possible values of time headway, there are totally $11^{10} * 5^9$ cases for a platoon of size 10. It will cost a huge amount of time to simulate all these cases. So we propose a threshold e, such that the simulation will keep adding new 100 cases with random sets of maximum deceleration and time headway until the collision probability does not change more than e compared with original simulation before we add new cases.

3. SIMULATION RESULTS

Since we have two two intentions for this thesis, assessing the effects of different parameters on safety of CACC as well as the improvement of safety from ACC to CACC, we take 11 cases of K_a (from 0 to 1 in a step of 0.1) for each assessment of one parameter.

We assess one parameter per subsection below in terms of probability of collision, expected impacts per collision, expected velocity at impacts and variance of spacing error which is depended on realizations. It is redundant to list variance of spacing error for all vehicle in all cases. Since the variances of spacing errors depended on realization for all following vehicles have the similar trends over time, we choose the variance of spacing error of third vehicle as our objective. We don't choose variance of spacing error of vehicle with large index for the reason that the differences between variances of spacing errors in different cases narrow with the increasing of index of vehicle.

3.1 Size of Platoon

We first assess the effect of size of platoon on the safety of CACC. We simulate the platoon with size of 5, 10 and 20 separately. Note that the size of platoon includes one leading vehicle with manual driving. As mentioned previously, the safety of control a strategy is evaluated by probability of collision in Figure 3.1, expected number of impacts per collision in Figure 3.2, expected velocity at impact in Figure 3.3 and variance of spacing error in Figure 3.4, 3.5 and 3.6.

We can get following facts under default parameter set S through the observation on Figure 3.1 to Figure 3.6.

- Size of a platoon does not significantly affect the probability of collision as shown Figure 3.1. Only in the cases where k_a is smaller than 0.2, platoons of smaller size would have less probability of collision than a platoon of large size.
- Under this parameter set S, the largest difference in the probability of collision between platoons of different sizes in Figure 3.1 happens where k_a is zero, i.e. platoon is under

ACC control strategy, which means CACC (or k_a) narrows the differences in probability of collision between platoons of different sizes. This decrease of differences also occurs in terms of expected number of collision and expected relative velocity at impact, which means CACC can lower the difference of safety metrics between platoon of different sizes.

- Probability of collision decreases first and increases slightly as k_a increases. In total, the probability of a collision is smaller with CACC systems than with ACC systems.
- In Figure 3.2, expected number of impacts per collision for platoon of size 5 is less than those for platoon of size 10 and size 20. However, the expected numbers of collisions for platoon of sizes 10 and 20 are nearly the same.
- Expected number of collisions decreases as k_a increases regardless of the platoon size. However, reduction of expected number of collisions along with an increase of k_a is larger when the platoon size is large. In other words, the enhancements in safety are more pronounced with platoons of CACC equipped vehicles when the platoon size is large.
- Figure 3.3 indicates that expected velocity at impact for a platoon of size 5 is larger than those for sizes 10 and 20, though the variance is small. Expected relative velocity at impacts for platoons of size 10 and 20 are correspondingly similar.
- With an increase in the size of a platoon, the gap in expected number of collisions and gap in expected relative velocity at impact reduces as shown in Figure 3.2 and 3.3; these figures indicate that most collisions happen in the first few vehicles in a string.
- From the perspective of variance of spacing error in Figure 3.4, Figure 3.5 and Figure 3.6, result is consistent with what has been shown previously, variances of spacing error of ACC are greater than those of CACC in all three platoons with different sizes.
- The peak value of variance for platoon under ACC with size 5 is less than that of platoon under ACC with larger size. And variances of spacing error for platoon under CACC are

indistinguishable for all size of platoons, which has been shown in a different way in Figure 3.2 and Figure 3.3.

- The peaks of variance appear at the same time for platoons of different sizes, say around 6 second. This implies that most collisions happen at the same time, regardless of the size of platoon.

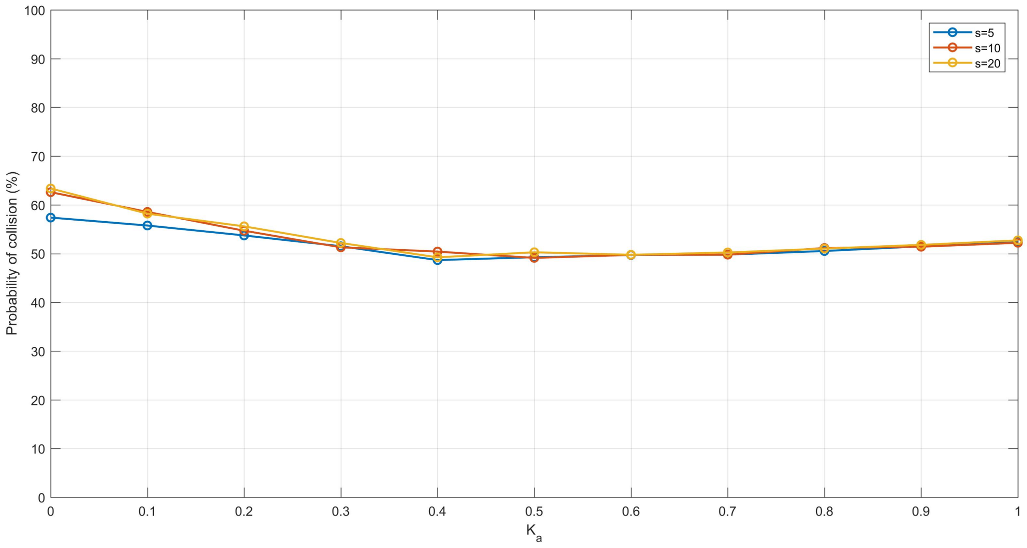

Figure 3.1: Probability of collision with different sizes of platoon

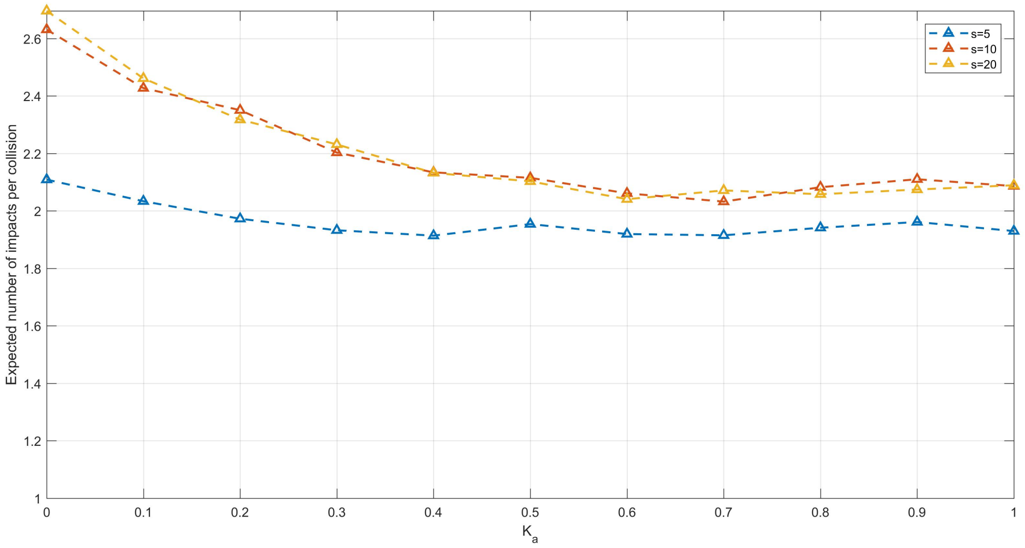

Figure 3.2: Expected number of impacts per collision with different sizes of platoon

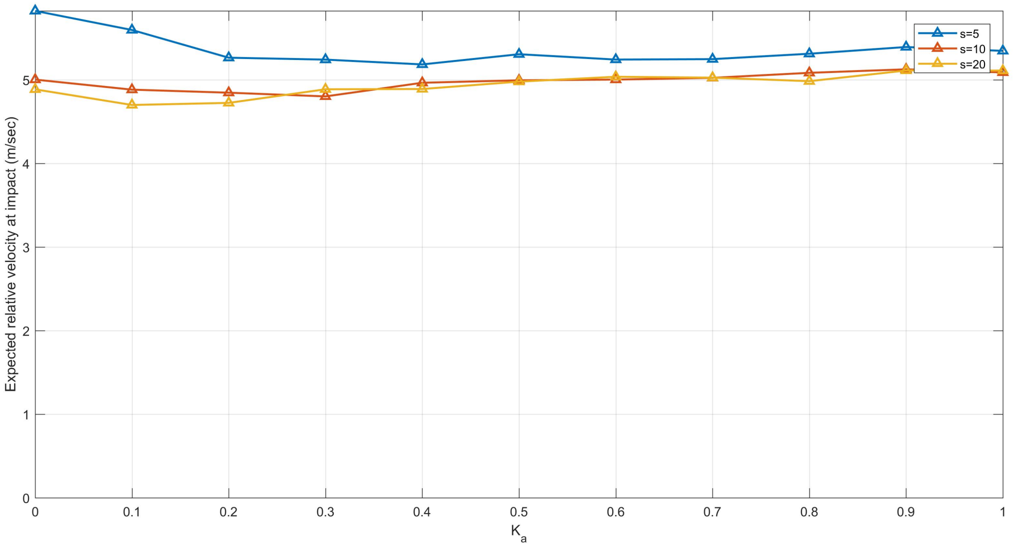

Figure 3.3: Expected velocity at impact with different sizes of platoon

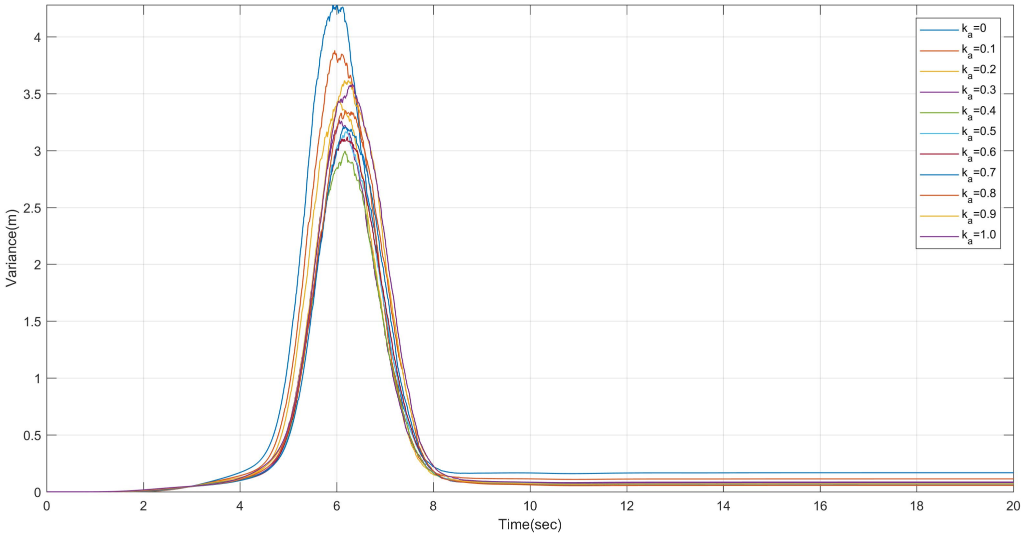

Figure 3.4: Variance of spacing error over time when size of platoon is 5

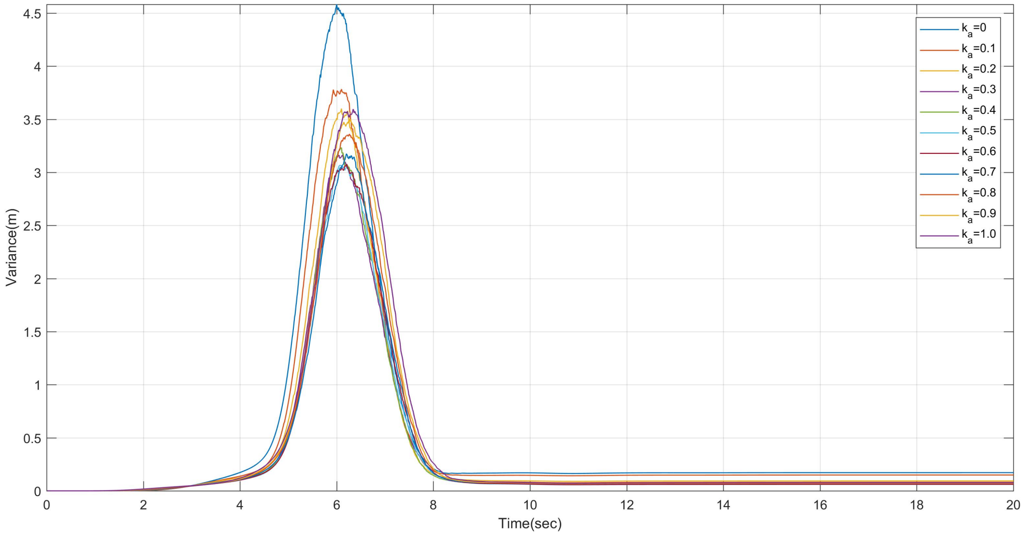

Figure 3.5: Variance of spacing error over time when size of platoon is 10

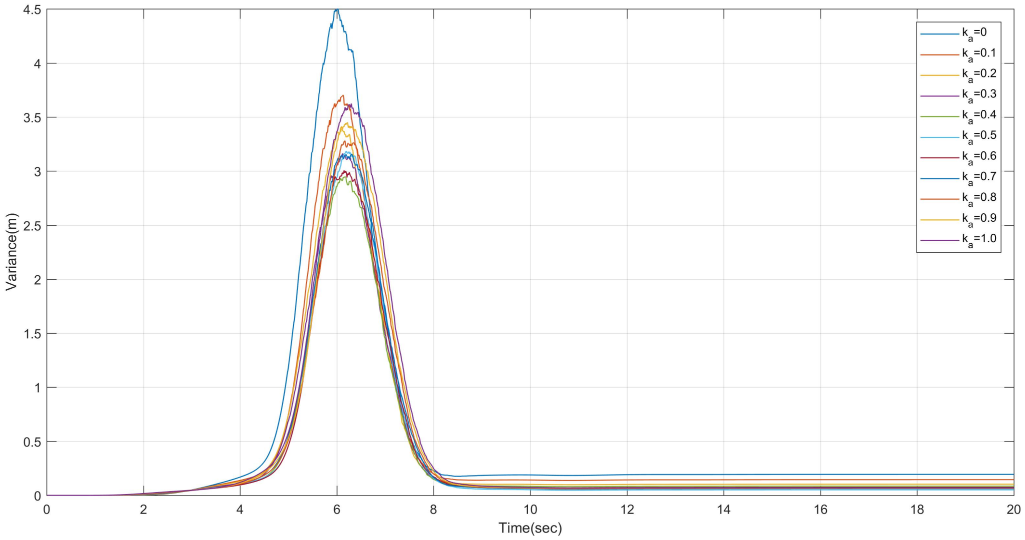

Figure 3.6: Variance of spacing error over time when size of platoon is 20

3.2 Initial Velocity

The second evaluated parameter is the initial velocity of vehicles in a platoon. All vehicles in the platoon have the same velocity initially. Based on an intuitive view, a higher value of initial velocity leads to a higher risk for collision. We analyze effects of initial velocity on the safety of a platoon of vehicles equipped with CACC systems for three different values of initial velocity, namely $20m/s$, $30m/s$ and $35m/s$. Usually, vehicles travel at $20m/sec$ in urban areas; typical highway speed are $30m/sec$ and $35m/sec$. As before, the safety of a control strategy is assessed by the following metrics: probability of a collision in Figure 3.7, expected number of collisions in Figure 3.8, expected relative velocity at impact in Figure 3.9 and variance of spacing error in Figure 3.10, 3.11 and 3.12.

From the figures, we can gather the following:

- As shown in Figure 3.7, an increase in k_a can reduce the probability of collision no matter how fast the platoon is moving initially. The reduction is more impressive when the initial velocity is small. The probability of collision can decrease more than 20 % when CACC systems are deployed in vehicles of a platoon with initial velocity of $20m/sec$ when compared to depolying ACC systems. On the contrary, when the initial velocity is $35m/sec$, CACC cannot even lower the probability of collision 10 %. Nevertheless, CACC can reduce the probability of a collision with any $k_a > 0$, however small it may be.

- In accordance with our intuition, the larger the initial velocity is, the higher is the probability of collision as shown in Figure 3.7.
- Figure 3.8 shows the expected number of collisions in CACC-equipped vehicle platoons is almost identical to that in Figure 3.7. An increment in initial velocity can significantly increase the expected number of collisions significantly. When the initial velocity increases to $30m/sec$ from $20m/sec$, there is roughly one more collision in the platoon. When the initial velocity increases further to $35m/sec$, expected number increases additionally by one, i.e. expected number of collisions increases with an increase in initial velocity.
- Acceleration feedback (given by $k_a \neq 0$) seems to lower the expected number of collisions, as can be seen in Figure 3.8. With the same initial velocity, ACC equipped vehicle platoons fare worse than their CACC-equipped vehicle platoon counterparts with respect to expected number of collisions.
- Expected relative velocity at impact is positively correlated to initial velocity in Figure 3.9. When the initial velocity is $20m/sec$, expected relative velocity at impact is $2m/s$; it increases to more than $6m/sec$ after initial velocity increases to $35m/sec$.
- Despite the significant difference in the expected velocity at impact made by initial velocity, k_a does not have a noticeable effect on expected relative velocity at impact.
- The observations about variance in Figure 3.10, Figure 3.11 and Figure 3.12 seem consistent with what we have from Figure 3.7, Figure 3.8 and Figure 3.9. Variance of spacing error for ACC-equipped vehicle platoons is larger than their CACC-equipped counterparts for each of the initial velocities considered.

- Peak value of variance in spacing error gets larger with initial velocity. The difference in the peak values o variance in spacing error among k_a gets smaller as initial velocity increases. In fact, peak value of variance of spacing error surges to more than $8\ m$ at $35\ m/sec$ from a value less than $1\ m$ at an initial velocity of $20\ m/s$.

- The time at which peak value of variance occurs also varies with the speed. The peak of variance appears around $5\ sec$ when the initial velocity is $20\ m/sec$, while it occurs at $6\ sec$ when initial velocity is $30m/sec$ and at $6.5\ \ sec$ when the initial velocity is $35\ \ m/sec$. In other words, when the initial velocity is lower, a majority of collisions happen earlier. While the initial part of the curves for all the three cases of initial velocities considered look nearly identical, the peak in variance is attained earlier when the initial velocity is lower.

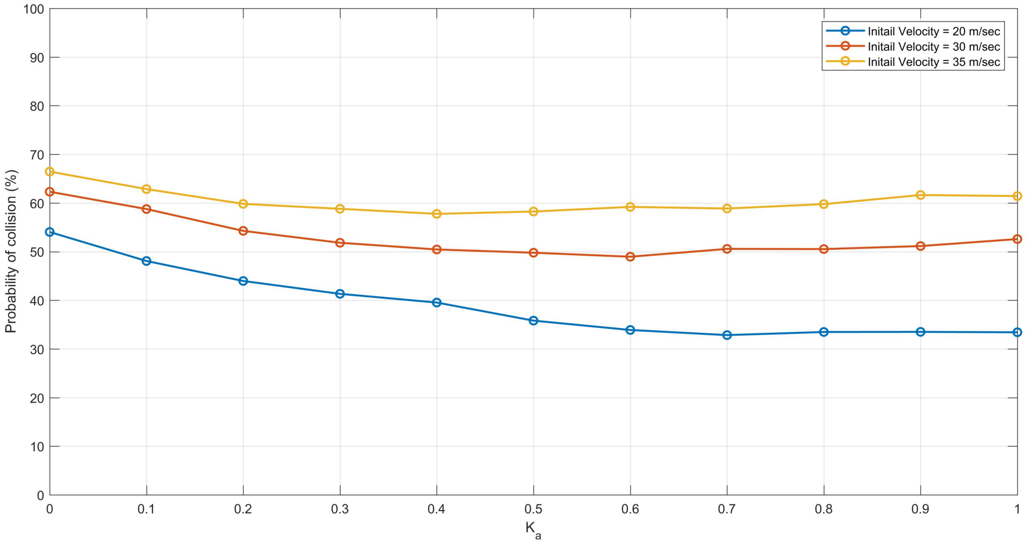

Figure 3.7: Probability of collision with different initial velocities

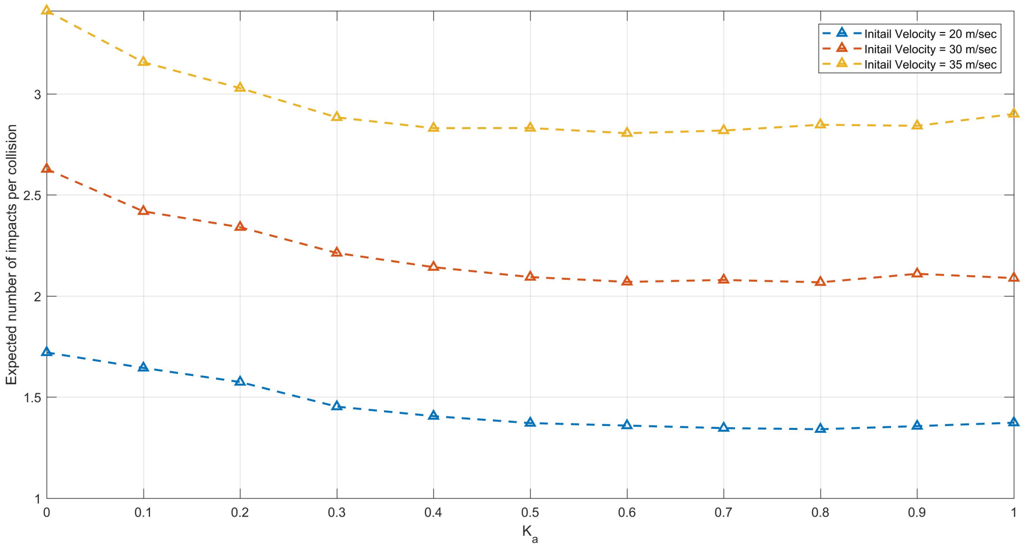

Figure 3.8: Expected number of impacts per collision with different initial velocities

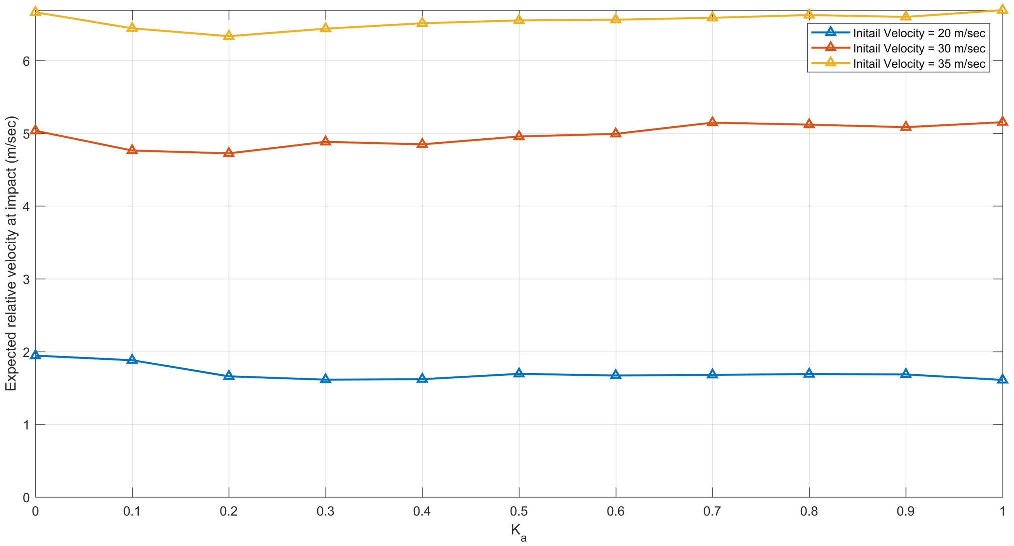

Figure 3.9: Expected velocity at impact with different initial velocities

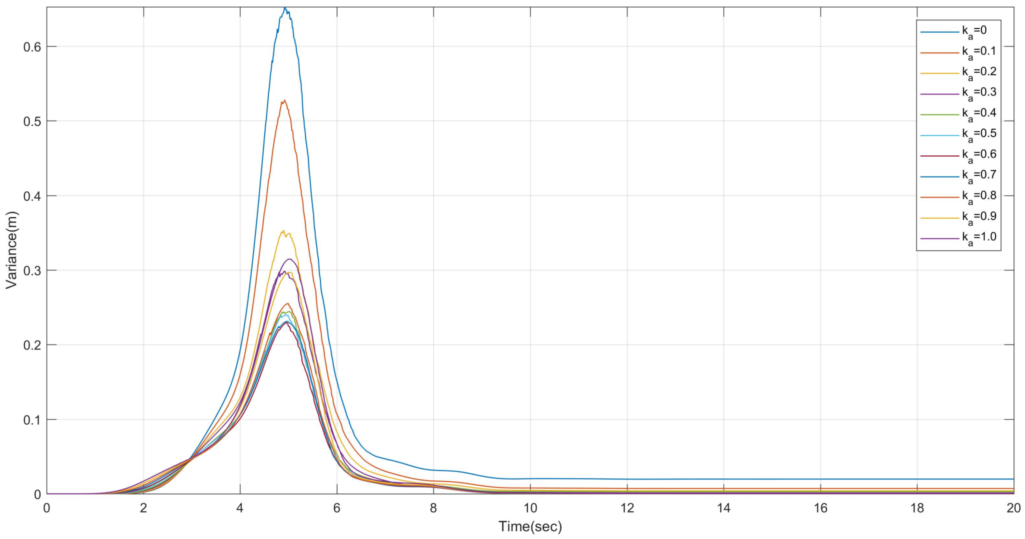

Figure 3.10: Variance of spacing error over time when initial velocity is $20m/sec$

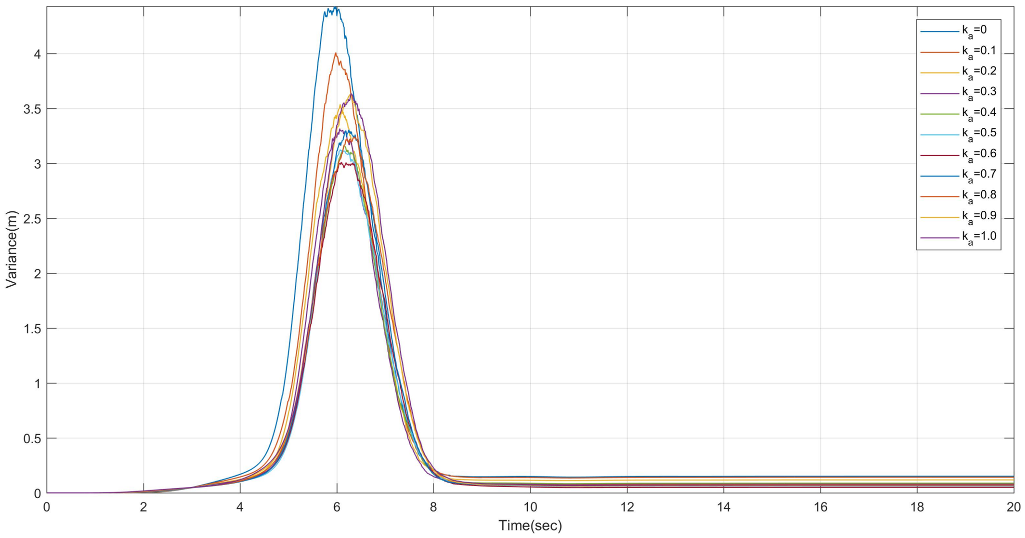

Figure 3.11: Variance of spacing error over time when initial velocity is $30m/sec$

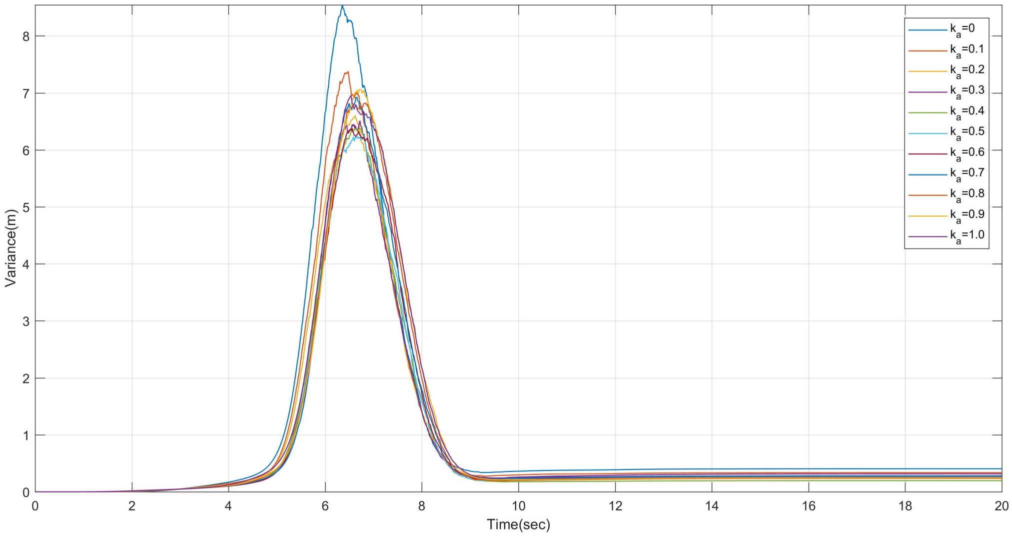

Figure 3.12: Variance of spacing error over time when initial velocity is $35m/sec$

3.3 Parasitic Latency

The third parameter we assess is actuation parasitic latency. The larger the actuation parasitic latency is, the more time it takes to modify accelerations of a vehicle to its corresponding control input. This is a vital parameter when one analyzes string stability of a platoon. The minimum time headway that can be employed by a platoon also depends on the parasitic latency [16]. As shown in following figures, it is also a critical reason for collisions. We consider three different values of latency - $0.2sec$, $0.4sec$ and $0.6sec$. As before, we employ the same metrics to assess safety - probability of collision in Figure 3.13, expected number of collisions in Figure 3.14, expected velocity at impact in Figure3.15 and variance of spacing error with three different values of parasitic latency in Figure 3.16, Figure 3.17 and Figure 3.18, corresponding to $0.2sec$, $0.4sec$ and $0.6sec$ respectively.

From the figures, we can infer the following:

- Parasitic latency increases the probability of a collision in a considerable way. Under ACC control strategy, probability of collision is 100% when latency become $0.6\ sec$ from $0.4\ sec$;

in other words, collision happens in every realization for this case. On the other hand, probability of collision lessens by more than 20% when the latency drops by 0.2 sec from 0.4 sec in Figure 3.13.

- Although one cannot gather from the simulation results shown here, one must choose integration time step of the differential equations to be much smaller than the parasitic latency to obtain numerically consistent results.

- In Figure 3.13, k_a seems to lower the probability of a collision; the effect is more pronounced when τ is larger.

- Latency also significantly influes the expected number of collisions, as shown in Figure 3.14. When τ is $0.6sec$, more than 5 collisions scenario on an average in a platoon of 10 ACC-equipped vehicles; this implies more than half of the vehicles collide on average. The corresponding expected number of collisions reduced to half that number when latency is 0.4 sec. Any further reduction in parasitic latency does not seem to reduce the expected number of collisions significantly.

- Unlike the probability of a collision, k_a's effect on expected number of impacts is noticeable. Especially when latency is high, as shown in Figure 3.14, the expected number of collisions decreases from a value more than 5 to 4 with increment of k_a from 0 to 1. When τ is 0.2 sec, CACC-equipped vehicle platoons seem to have lower value for the expected number of collision than their ACC-equipped counterparts.

- Figure 3.15 seems to depict anamalous results. With an increase in the values of latency, expected relative velocity at impact decreases. It seems as if an increase in latency can improve safety in terms of expected relative velocity at impact. However, the reduction of expected velocity at impact results from the surge of expected number collisions. Note that when multiple collisions happen in one platoon, it is common that the impact that happens at the front of a platoon always have a larger relative velocity at impact than a impact that happen at the back of a platoon. Basically, relative velocity at impact in a platoon decreases in the direction pointing to the tail of platoon. Since the expected velocity is calculated by dividing the sum of all relative velocity at impacts by total number of impacts in the simulation, and lots of small relative velocities at impact are included when computing the expected relative velocity at impact when latency is $0.6sec$, expected velocity at impact of high latency is less than that of low latency. Only the expected velocity at impact itself is not sufficient to show whether a control strategy is better.

- Even though the effect of τ on expected velocity does not imply the improvement of safety by shortening latency, it is clear that k_a does make a positive difference on expected relative velocity at impact when latency is high. This is consistent with what we discussed in Figure 3.14, k_a (or CACC) improve the safety greatly with respect to expected number of collisions and expected relative velocity at impact. While τ is small, increasing k_a still reduces expected relative velocity at impact, even though the reduction is small.

- Variances of spacing error in Figure 3.16, Figure 3.17 and Figure 3.18 indicate similar conclusions. In all these three figures, variances of spacing error when k_as are 0 are larger than those when k_as are not zero, which means CACC contributes to safety more than ACC whenever latency is high or low. The difference between the peak value of variance of spacing error with k_a and the peak value of variance of spacing error without k_a enlarges with increments of latency. k_a benefits more in the case where latency is higher.

- Peaks of variance of spacing error growth with increase of latency, no matter how large k_a is. For instance, peak value of variance when k_a is 0 is less than 3 in Figure 3.16 and peak value of variance when k_a is 0 is more than 4 in Figure 3.17. And that value surge to more than 7 when τ is $0.6sec$. This points out the increase of latency leads to deterioration of safety.

- One property we have not talked about but is also important and noticeable in Figure 3.18 is the variance value when time goes to infinity. It's clear that all vehicles in platoon will stop finally. And by applying our control strategy in equation 2.2 and equation 2.3 and algorithm shown in Figure 2.3 (especially the policy forcing vehicle moving forward after its stopping without impact), spacing error will converge to zero when time goes to infinity if no collision happens. Therefore, the variance at infinity is caused by collision. And variance at infinity under ACC is larger than that under CACC, which is most manifest when τ is $0.6\ sec$. Variances at infinity when τ is higher are larger than the variances at infinity when τ is lower for the same corresponding k_a. Besides, difference between variance at infinity when τ is high and variance at infinity when τ is low lessens with increment of k_a through Figure 3.16, Figure 3.17 and Figure 3.18.

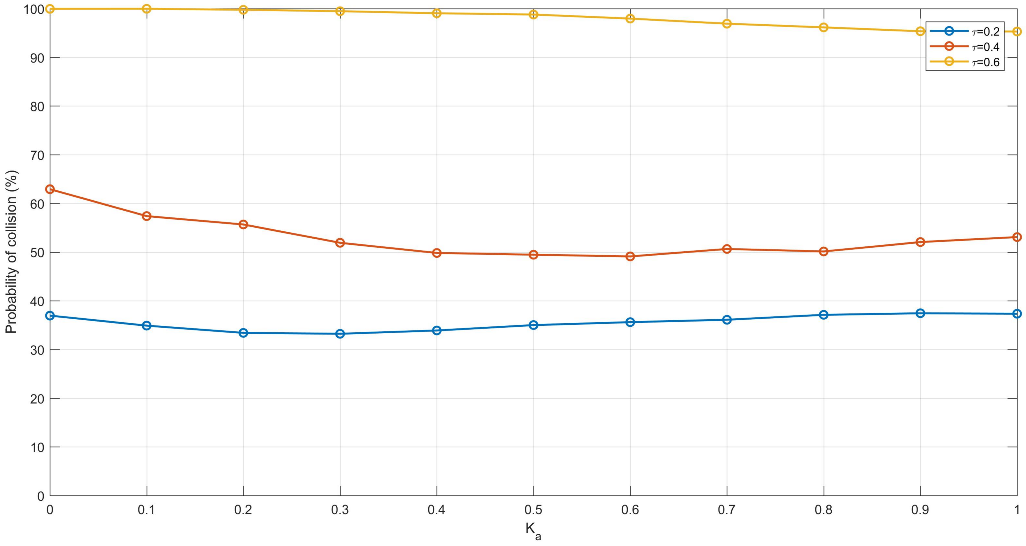

Figure 3.13: Probability of collision with different parasitic latency

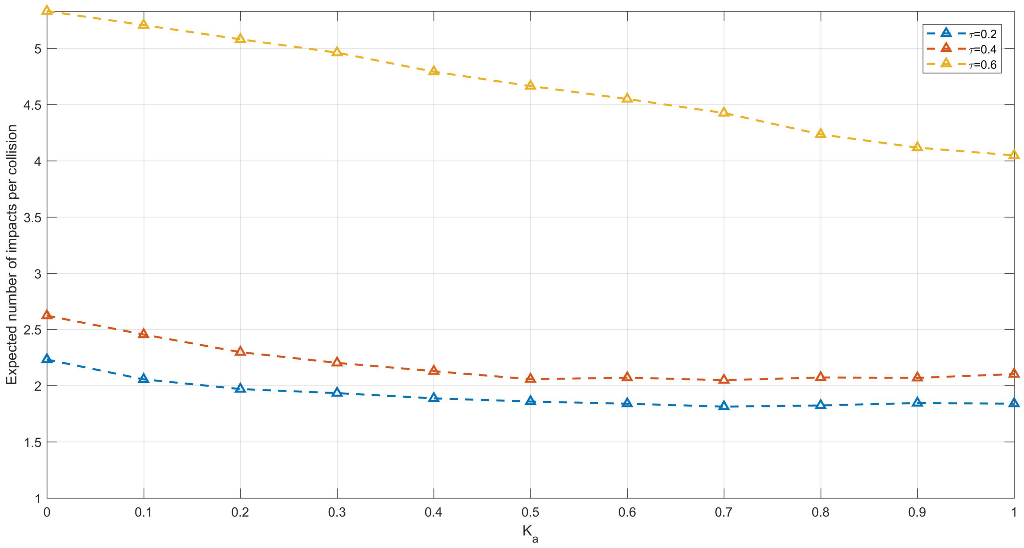

Figure 3.14: Expected number of impacts per collision with different parasitic latency

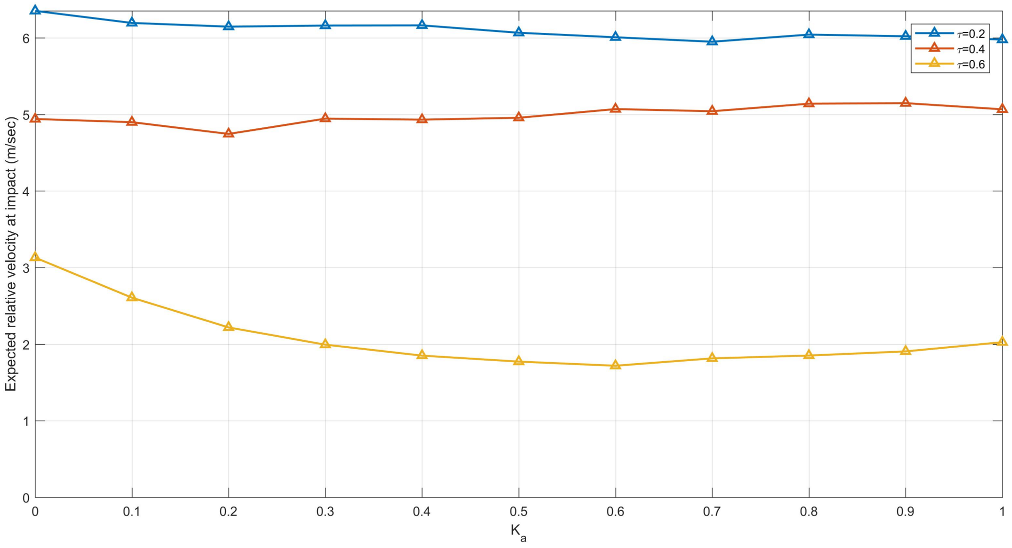

Figure 3.15: Expected velocity at impact with different parasitic latency

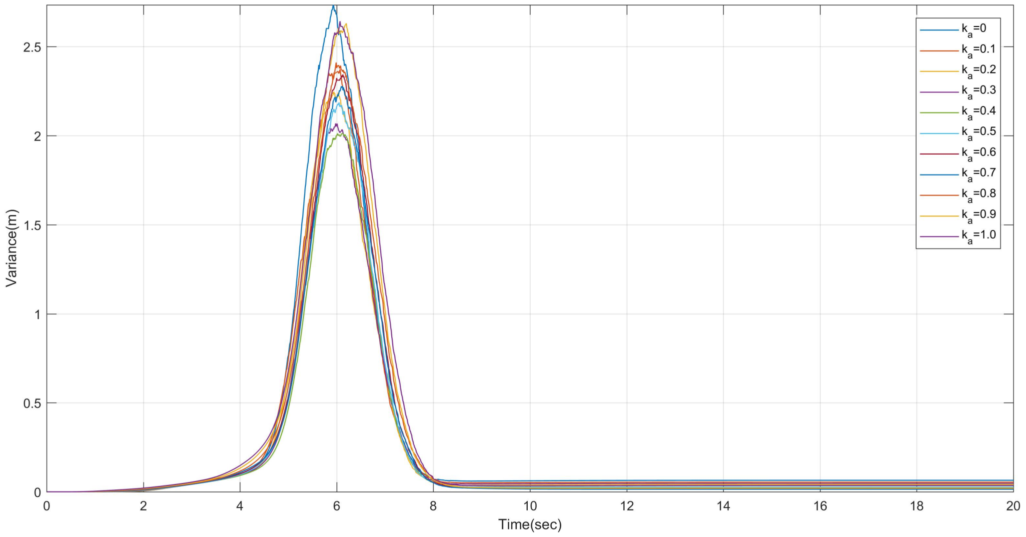

Figure 3.16: Variance of spacing error over time when parasitic latency is $0.2sec$

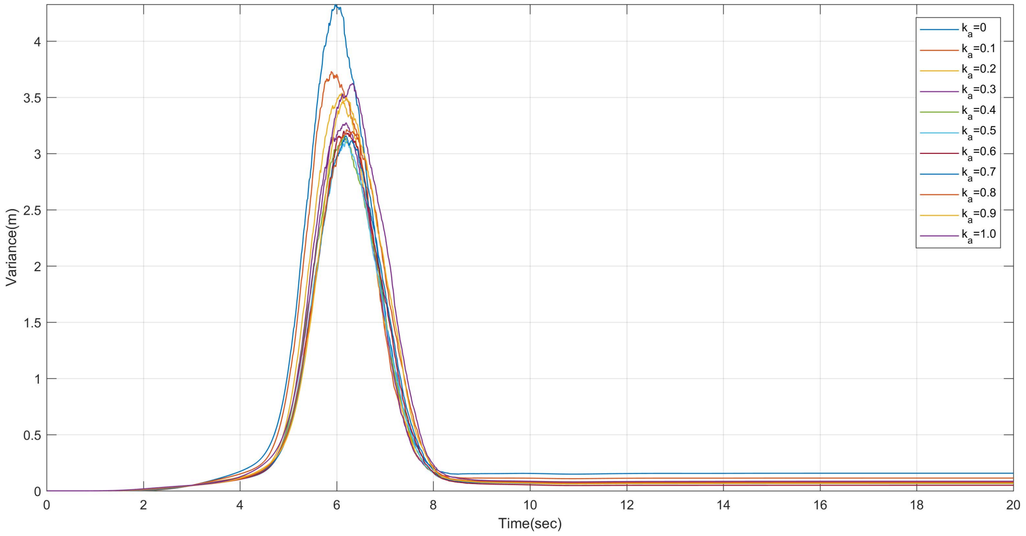

Figure 3.17: Variance of spacing error over time when parasitic latency is $0.4sec$

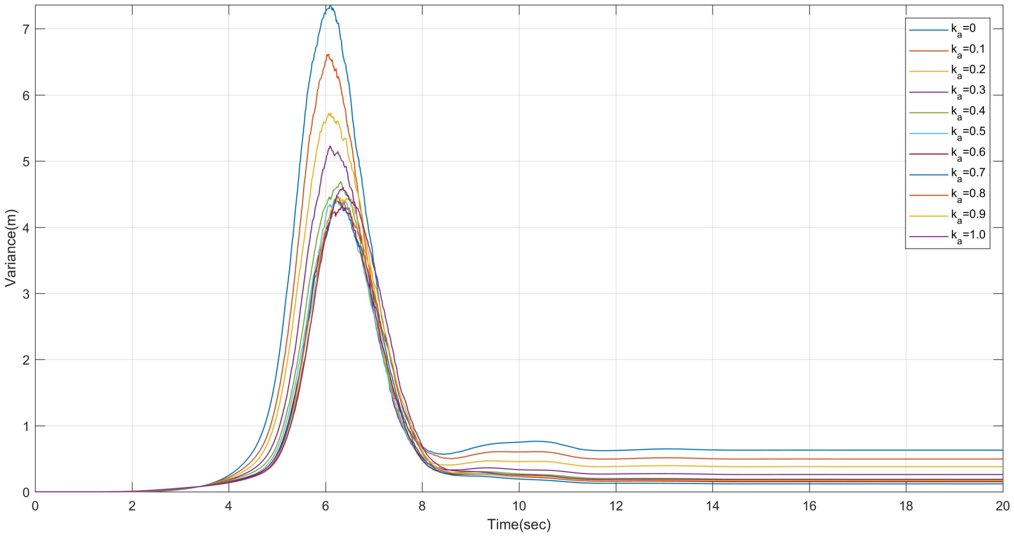

Figure 3.18: Variance of spacing error over time when parasitic latency is $0.6sec$

3.4 Packet Drop Rate

We assess packet dropping rate as the fourth feature that may affect the safety of CACC. Note that we assume packet drops only happen in the communication between vehicles, i.e. only massages of k_a may get missed. Basically, packet dropping rate doesn't effect safety of ACC.

As what we have assessed, we evaluate effect of packet dropping rate on safety with respect to probability of collision is Figure 3.19, expected number of impacts per collision in Figure 3.20, expected relative velocity at impact in Figure 3.21 and variances of spacing error with different packet dropping rates in Figure 3.22, Figure 3.23 and Figure 3.24. We take three packet dropping rate, 0.3, 0.5 and 0.7. Consider that large packet dropping rate represents bad communication condition and high probability of losing messages.

One can make following conclusions from Figure 3.19 to Figure 3.24.

- Packet dropping rate doesn't make any difference on probability of collision, expected number of impacts per collision and expected relative velocity at impact under ACC. This makes sense, because packet dropping rate only affects communication between vehicle.

- For a same k_a, probability of collision increase with increment of packet dropping rate. And the differences between probabilities of collision with various packet dropping rates amplify with growth of k_a in Figure 3.19.
- Whenever packet dropping rate is low or high, probability of collision in cases with k_a is always less than the probability of collision under ACC. And the less packet dropping rate is, the more impressive the reduction of probability contributed by k_a is.
- We can see that, if a k_a is eligible to reduce the probability of collision for a certain packet dropping rate, it won't rise the probability of collision for any packet dropping rate, even though the packet dropping rate is high.
- In Figure 3.20, lowering of packet dropping rate lessens expected number of impacts per collision a lot under CACC. The effect is impressive in the case where k_a is large. The deduction of expected number of impacts per collision caused by increasing k_a from 0 to 1 enlarges when we decreasing packet dropping rate.
- Almost the same as previous statements, any non-trivial k_a lessens expected number of impacts per collision with respect to ACC with any packet dropping rate.
- As shown in Figure 3.21, enlargement of packet dropping rate can also increase expected relative velocity at impact with non-zero k_a. This effect is more noticeable when k_a is higher. On the other hand, lowering of packet dropping rate is an effective way to reduce expected velocity at impact.
- When packet dropping rate is 0.5, the effect of k_a on expected relative at impact is unnoticeable in Figure 3.21. When packet dropping rate is low, k_a has a positive influence on reducing expected relative velocity at impact. And the interesting fact is that k_a will take a negative effect on reducing expected relative velocity at impact in Figure 3.21. Sudden changes of control input may be one of reasons for this.

- Peak values of variance of spacing error with zero k_a are same in Figure 3.22, Figure 3.23 and Figure 3.24, which means packet dropping rate doesn't have any effect on ACC.
- Peak values of variance of spacing error under ACC is larger than that under CACC in all three cases. And with increasing of packet dropping rate, the peak values of variance under CACC are getting closer to the peak value of variance under ACC. Besides, gaps among peak values of variance for different k_a narrow with increment of packet dropping rate. In other words, with enlargement of packet dropping rate, platoons with different k_a are more likely to perform identically.

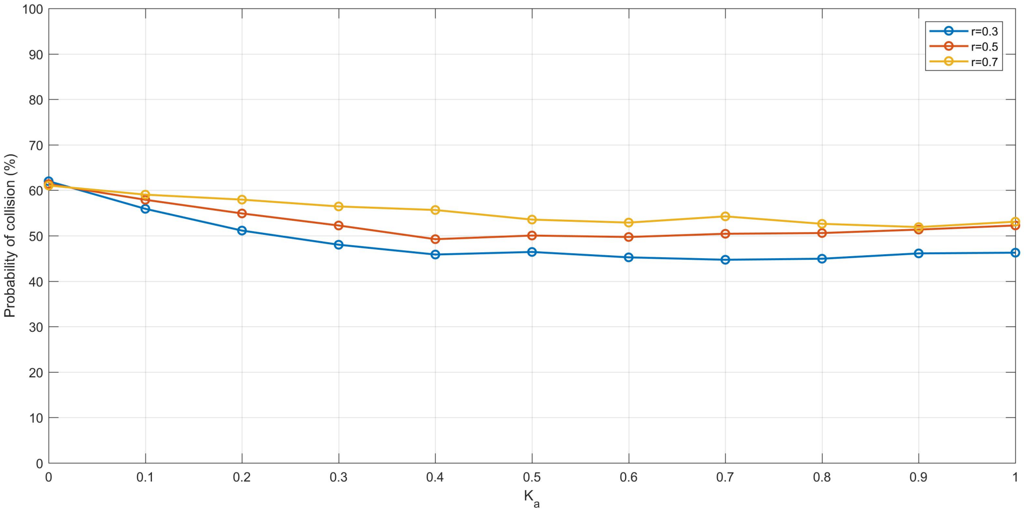

Figure 3.19: Probability of collision with different packet dropping rates

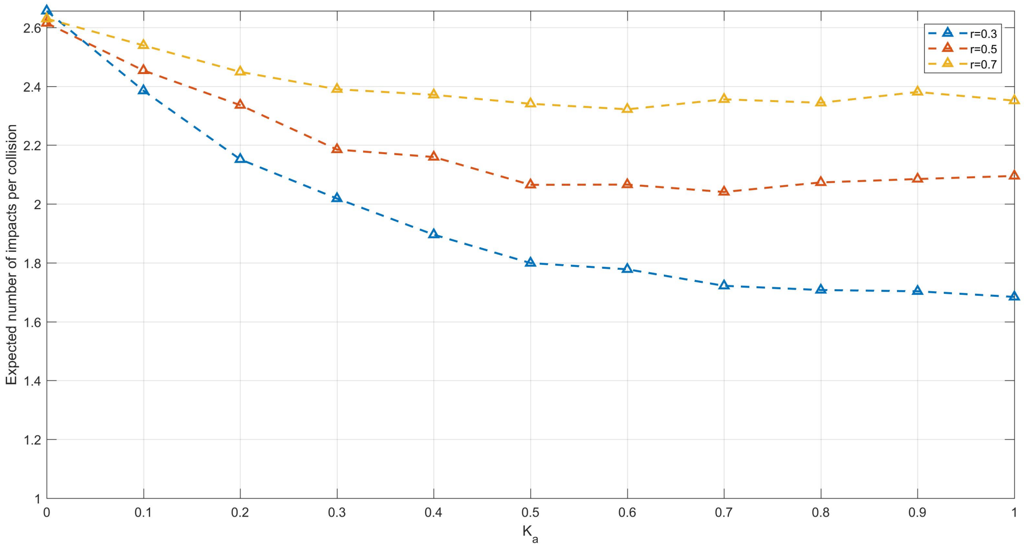

Figure 3.20: Expected number of impacts per collision with different packet dropping rates

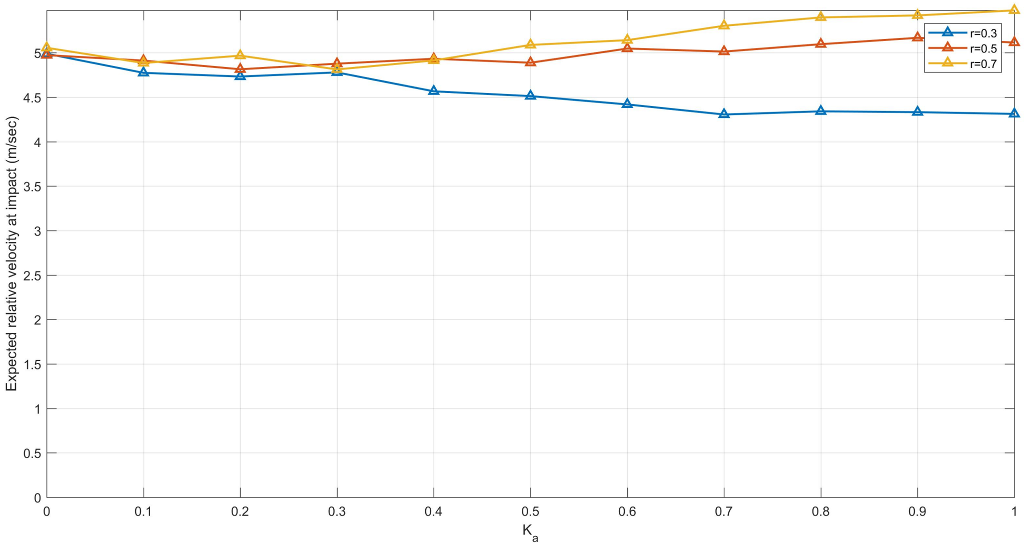

Figure 3.21: Expected velocity at impact with different packet dropping rates

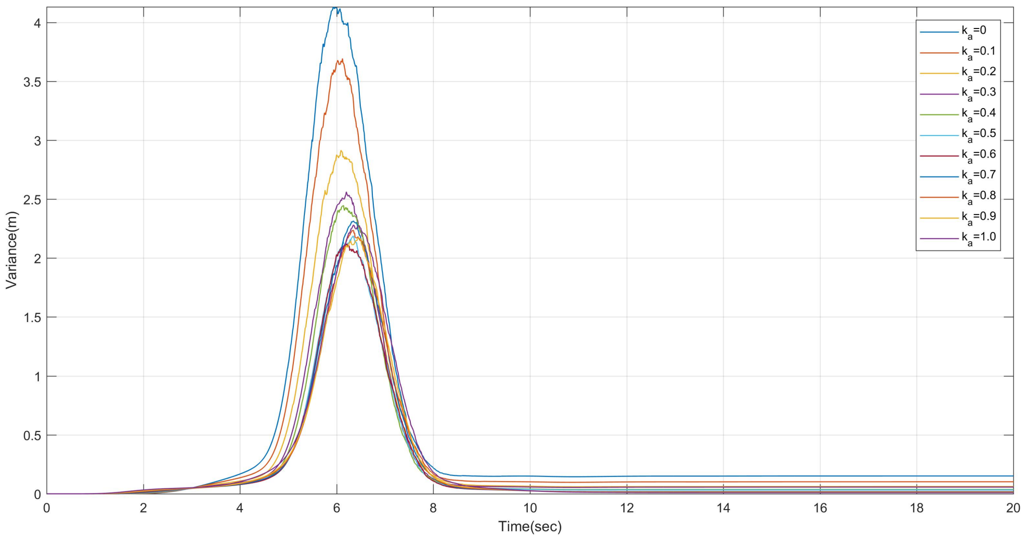

Figure 3.22: Variance of spacing error over time when packet dropping rate is 0.3

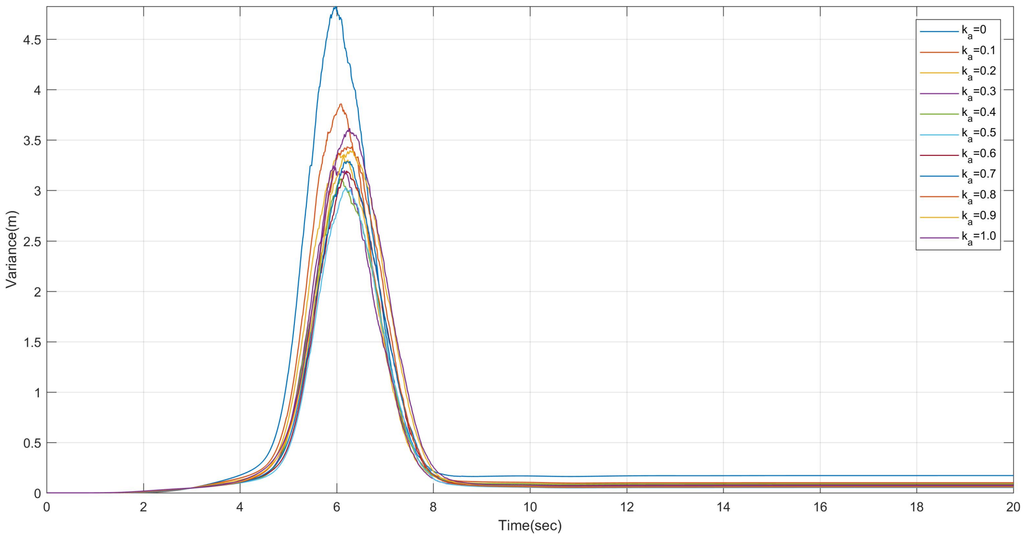

Figure 3.23: Variance of spacing error over time when packet dropping rate is 0.5

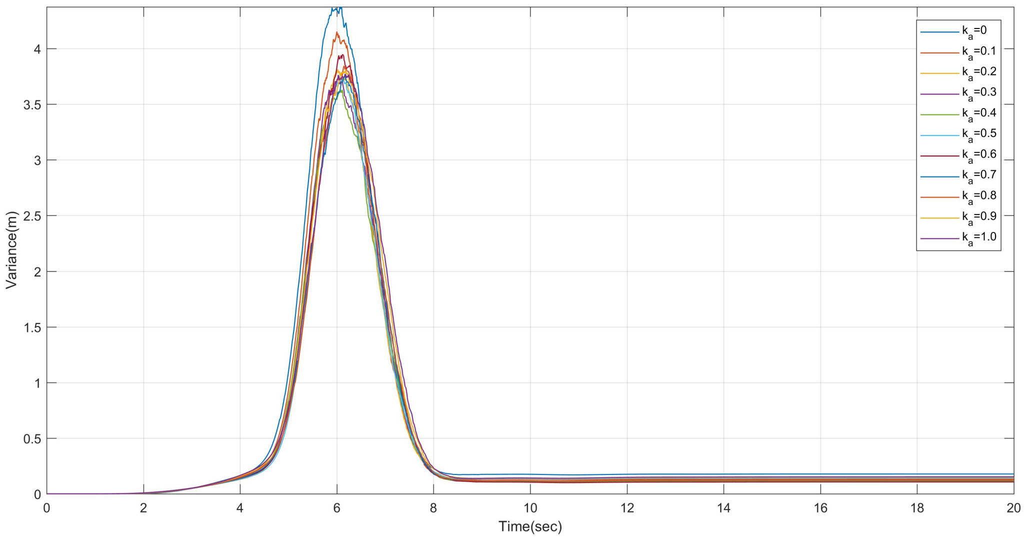

Figure 3.24: Variance of spacing error over time when packet dropping rate is 0.7

3.5 Length of Vehicle

The fifth parameter we evaluate is length of vehicle in the platoon. Since we assume length of vehicle in a string is homogeneous, we just set a constant as the length of vehicle in each case. We choose $3m$, $10m$ and $20m$ as three lengths of vehicle, representing length of regular car, length of medium truck and length of combinations of truck and trailer respectively.

We also apply probability of collision in Figure 3.25, expected number of impacts per collision in Figure 3.26, expected relative velocity at impact in Figure 3.27 and variance of spacing error in Figure 3.28, Figure 3.29 and Figure 3.30 to assess the safety of CACC.

Following statements are found by analyzing these figures.

- Length of vehicle doesn't alter probability of collision. For any k_a, probabilities of collision are same regardless of length of vehicle in Figure 3.25. Therefore, it also doesn't change the fact that k_a reduces probability of collision.

- Besides probability of collision, expected number of impacts per collision also remains same with changing of length of vehicles in Figure 3.26. Length of vehicles doesn't alter the fact that k_a lessens expected number of impacts per collision as well.

- Additionally, length of vehicles has no effect on expected relative velocity at impact. Expected relative velocities at impact with different length of vehicle have the same trend in Figure 3.27 and don't vary a lot with growth of k_a.

- Alike statements above, length of vehicle doesn't make any difference on variance of spacing error either. Variances of spacing error are totally identical in Figure 3.28, Figure 3.29 and Figure 3.30. And in every case, k_a contributes to lowering variance of spacing error. Based on above statements, length of vehicle doesn't alter the improvement of CACC on safety.

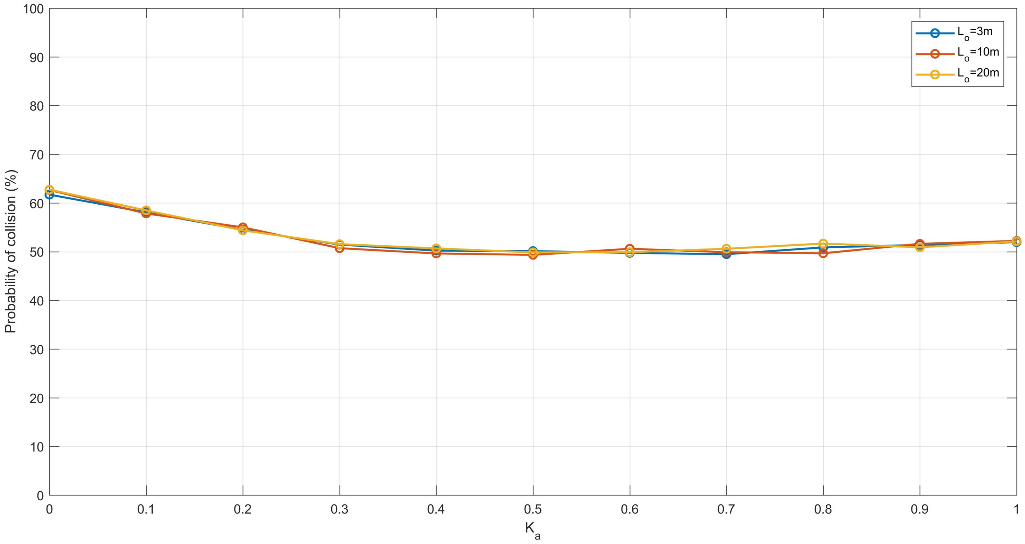

Figure 3.25: Probability of collision with different lengths of vehicle

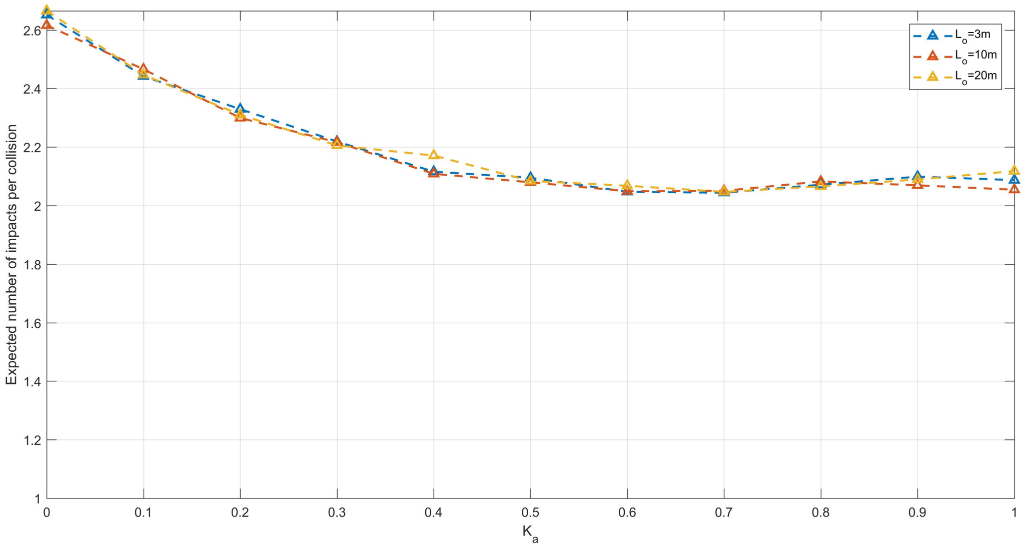

Figure 3.26: Expected number of impacts per collision with different lengths of vehicle

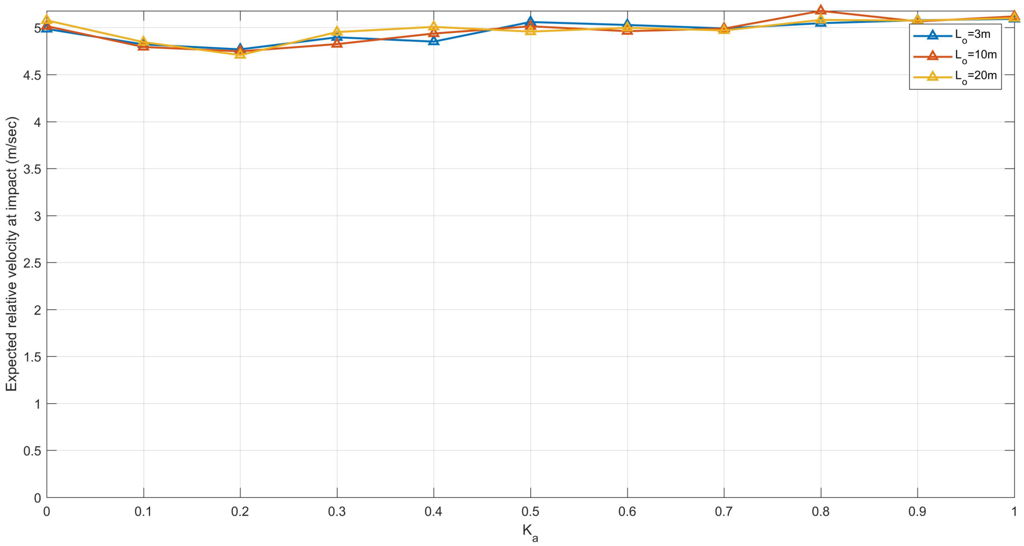

Figure 3.27: Expected velocity at impact with different lengths of vehicle

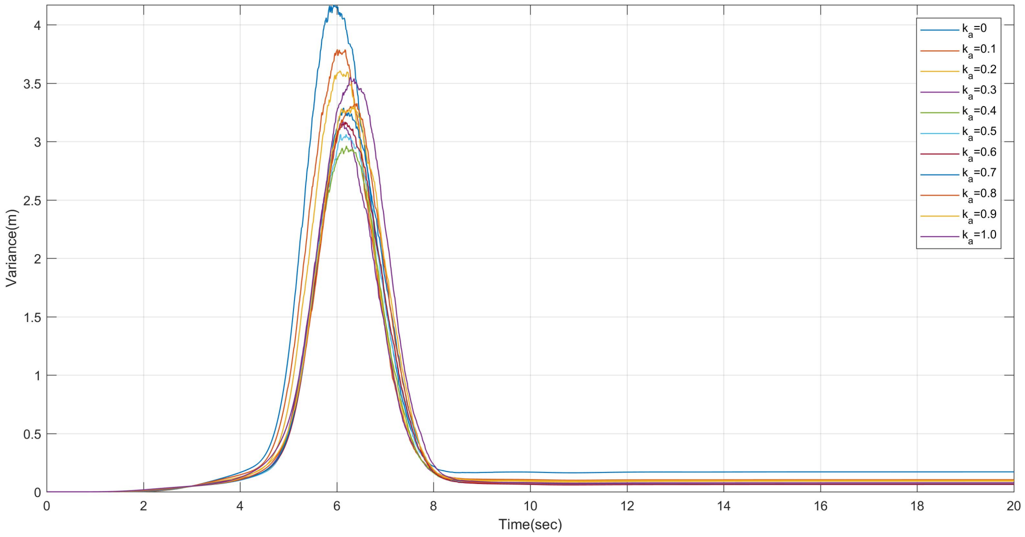

Figure 3.28: Variance of spacing error over time when length of vehicle is $3m$

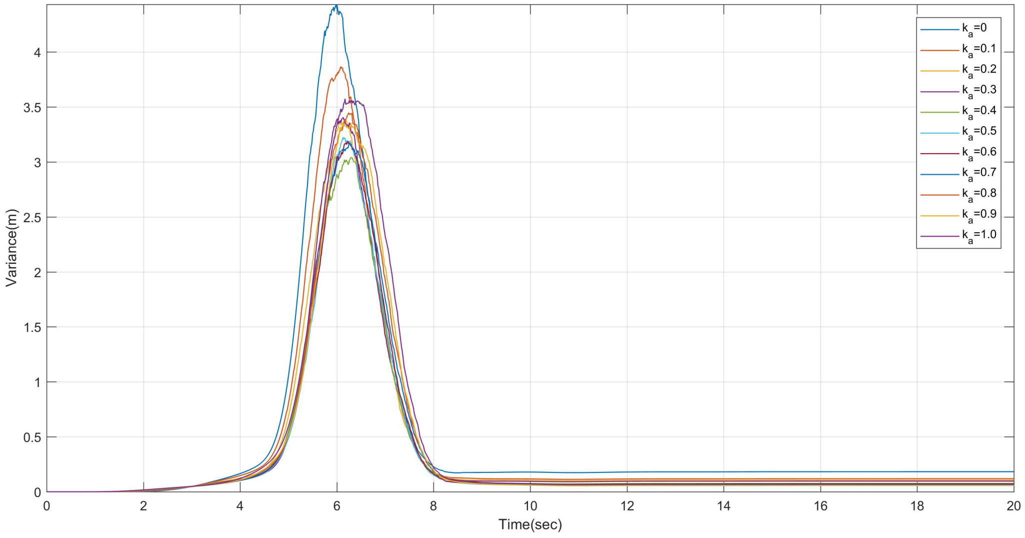

Figure 3.29: Variance of spacing error over time when length of vehicle is $10m$

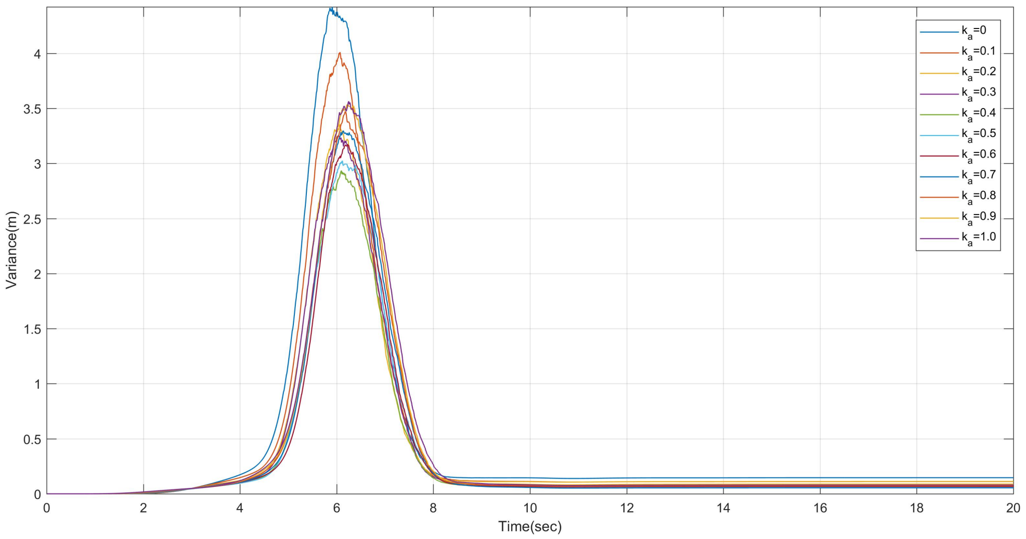

Figure 3.30: Variance of spacing error over time when length of vehicle is $20m$

3.6 Control Gains

Since we have assessed the effect of parameters on safety with various k_as previously, we mainly focus on the effects of k_p and k_v on safety if CACC in this section. As for other parameters that we don't mention in this section, they are the same as their corresponding default values in set S.

We first examine influences of various k_ps on probability of collision, expected number of impacts per collision and expected relative velocity at impact in cases with different k_as. Then we test the improvement of various k_vs as what have done for k_p. Finally, we try to get a "safety set" of gains (k_p, k_v, k_a) in which the probability of collision will be less than a threshold.

3.6.1 Position Gain K_p

We alter k_p from 0 to 3 in a step of 0.2, and k_a from 0 to 1 in a step of 0.2. We plot properties that we consider with respect to k_p instead of k_a in Figure 3.31, Figure 3.32 and Figure 3.33. Each lines represents a certain value of k_a in these figures. Figure 3.31, Figure 3.32 and Figure 3.33 show the effect of k_p on probability of collision, expected number of impacts per collision and expected relative velocity at impact with different k_a respectively.

Following statements are proposed based on the observation of figures.

- In the range from 0 to 3, k_p is eligible to lower probability of collision for any value of k_a. The larger the k_a is, the minor the effect of k_p is on probability of collision. That is to say increment of k_p improves ACC more than CACC in term of probability of collision.

- Probabilities of collision under ACC are usually greater or equal to corresponding probability of collision under CACC with same k_p. And it's clear that for small k_ps, with growth of k_a, probabilities of collision at a constant k_p reduce.

- When k_p is small, the reduction of probability of collision by increasing k_a is significant, which means CACC can improve safety in terms of probability of collision a lot. While k_p is large, the probability of collision of a platoon under ACC is similar with the probability of collision for a platoon under CACC. In the range from 0 to 3, increment of k_p narrows the gap between ACC and CACC with respect to probability of collision.

- Same as probability of collision, k_p also has dramatic influence on expected number of impacts per collision, especially when k_a is small. In Figure 3.32, expected number of impacts per collision for a platoon under ACC reduces more than 6 by enlarging k_p from 0 to 3. And this kind of reduction caused by increment of k_p fades away with growth of k_a. When k_a is 0.8, expected number of impacts per collision almost remain same along with increasing of k_p. Farther more, enlargement of k_p even increases expected number of impacts per collision when k_a is 1 in Figure 3.32.

- Reduction of expected number of impacts per collision by increasing k_a is notable, especially when k_p is small. k_a is eligible to lessen expected number of impacts per collision for all k_p in the range from 0 to 3. Along with growth of k_p, effects of k_a weakens.

- In Figure 3.33, expected velocity at impact over various k_p behaves in the way as expected number of impacts per collision does. Increment of k_p also narrows the differences among expected relative volecities at impact with various k_as. But expected relative velocity at impact is more sensitive to k_p. Expected relative velocity at impact under ACC and expected relative velocity at impact under CACC are identical when k_p is 1.4. Besides, k_p contributes a significant reduction of expected velocity at impact when k_a is zero. And k_p's influence on expected velocity at impact disappear gradually with enlargement of k_a. Overall, CACC is better than or equal to ACC in terms of expected relative velocity at impact when k_p changes between 0 and 3.

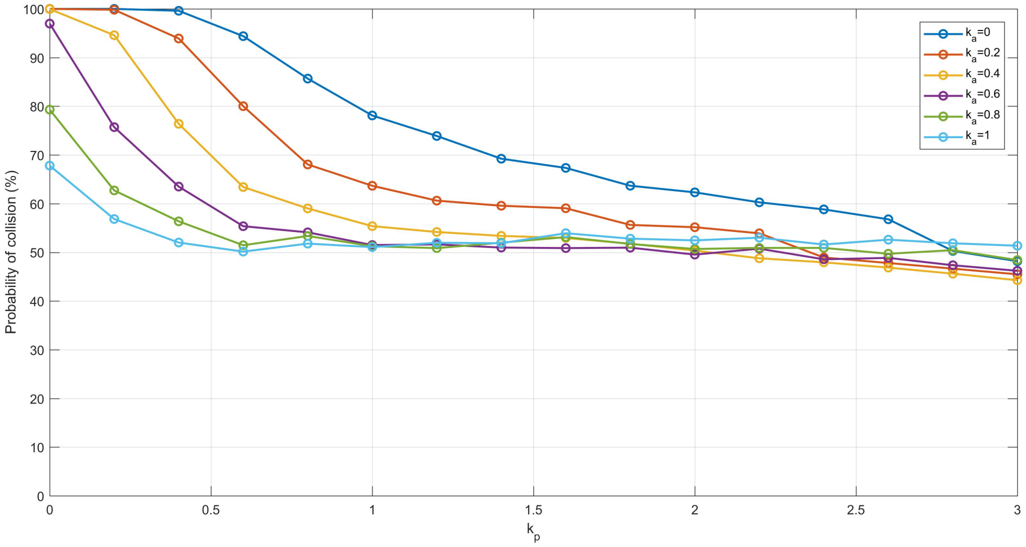

Figure 3.31: Probability of collision with different k_p

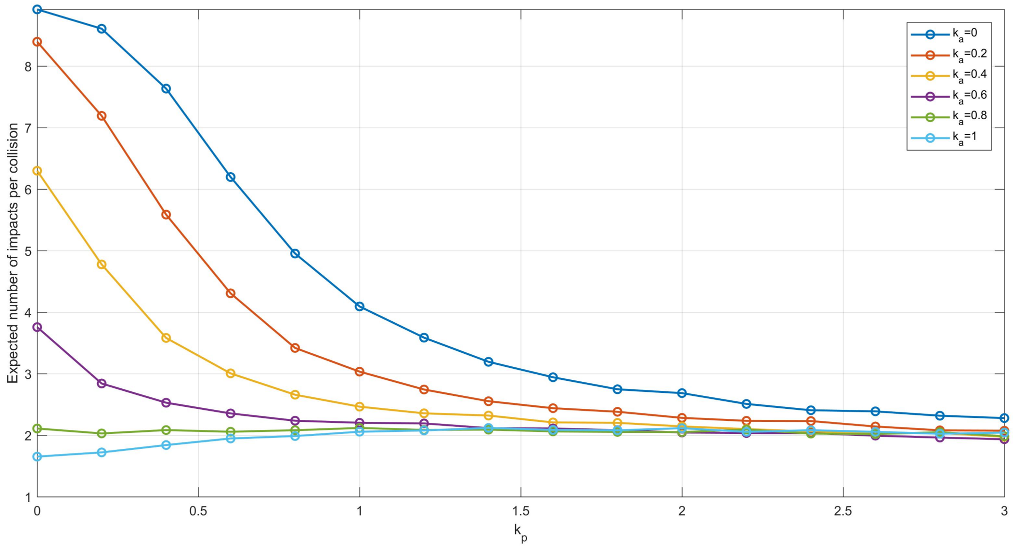

Figure 3.32: Expected number of impacts per collision with different k_p

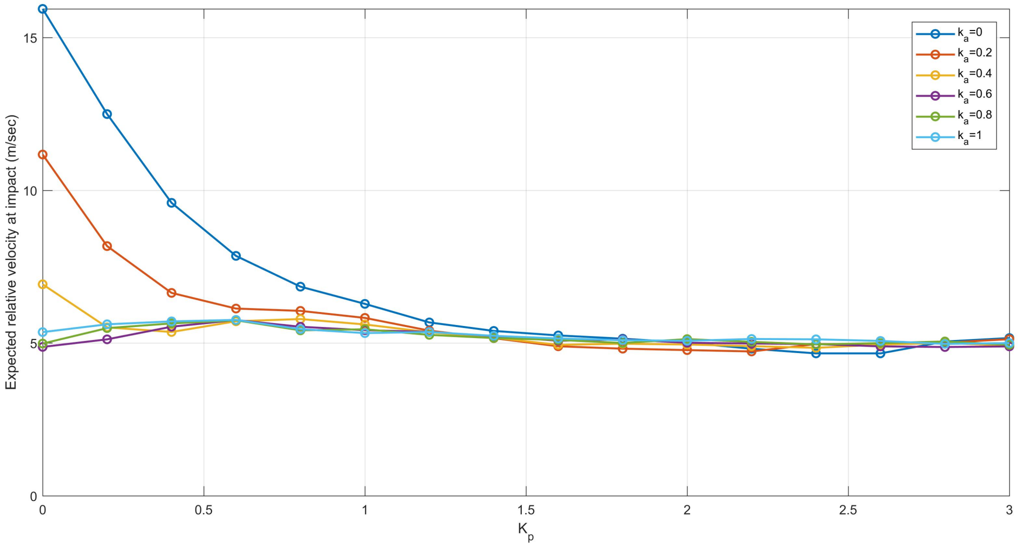

Figure 3.33: Expected velocity at impact with different k_p

3.6.2 Velocity Gain K_v

We change k_v from 0 to 3 in a step of 0.2, and k_a from 0 to 1 in a step of 0.2. Identically, we plot probability of collision, expected number of impacts per collision and expected relative velocity at impact with respect to k_p instead of k_a in Figure 3.34, Figure 3.35 and Figure 3.36 respectively. Each lines represents a certain value of k_a in these figures.

We can get following observations from these figures.

- k_v is one of crucial factors that affect probability of collision. Probability of collision of platoons under ACC drops from 100% to 20% when k_v grow from 0 to 1.5. And similar reduction also happens on the probability of platoons under CACC. While being larger than 1.5, k_v alters probability of collision slightly.

- For any k_v in the range from 0 to 3, probability of collision of platoons under CACC is always less than or equal to that of platoons under ACC.

- Expected number of impacts per collision in Figrue 3.35 has the same trend as probability of collision shown in Figure 3.34. k_v reduces expected number of impacts per collision for any constant k_a in a manner that expected number of impacts per collision drops fast when k_v is small and slowly when k_v is high in the range between 0 and 1.

- k_v in the range from 0 to 1 also doesn't change the fact that platoons under CACC have smaller expected number of impacts per collision than platoons under ACC. And the difference between expected number of impacts per collision of platoons under ACC and that of platoons under CACC narrows with increasing of k_v.

- Expected velocity at impact in Figure 3.36 is interesting. Along with increment of k_v from 0 to 3, expected velocity at impact drops first and then rise up for any k_a. As we have talked before about expected velocity at impact with different parasitic latency, this increment of expected velocity at impact results from the decrease of expected number of impacts per collision. Since minor impacts happen less when k_v is high, average expected velocity at impact enlarges.

- Expected relative velocity at impact of platoons under ACC is much larger than that if platoons under CACC when k_v is less than 0.5. When k_v is larger than 0.5, expected relative velocity at impact of platoons under ACC is almost identical to that of platoons under CACC.

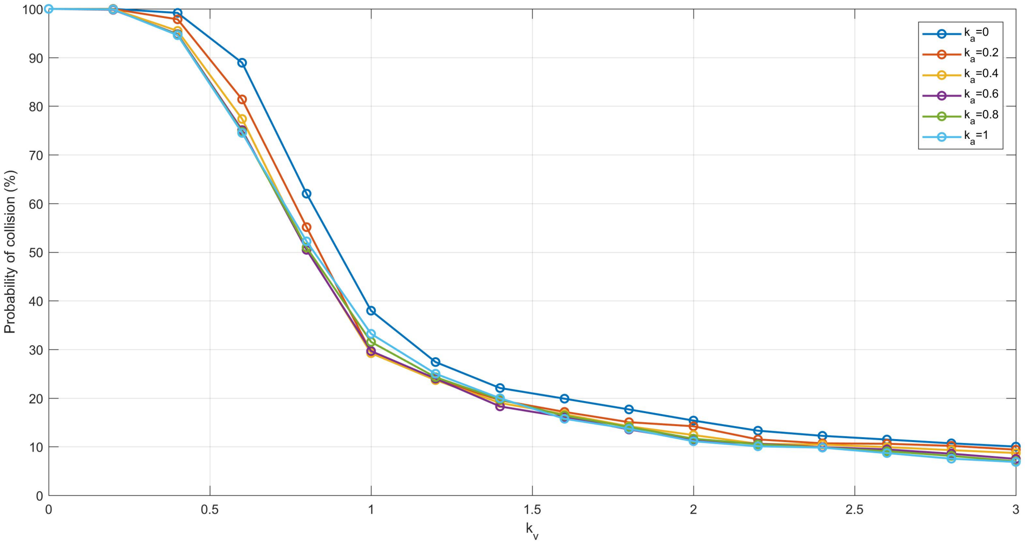

Figure 3.34: Probability of collision with different k_v

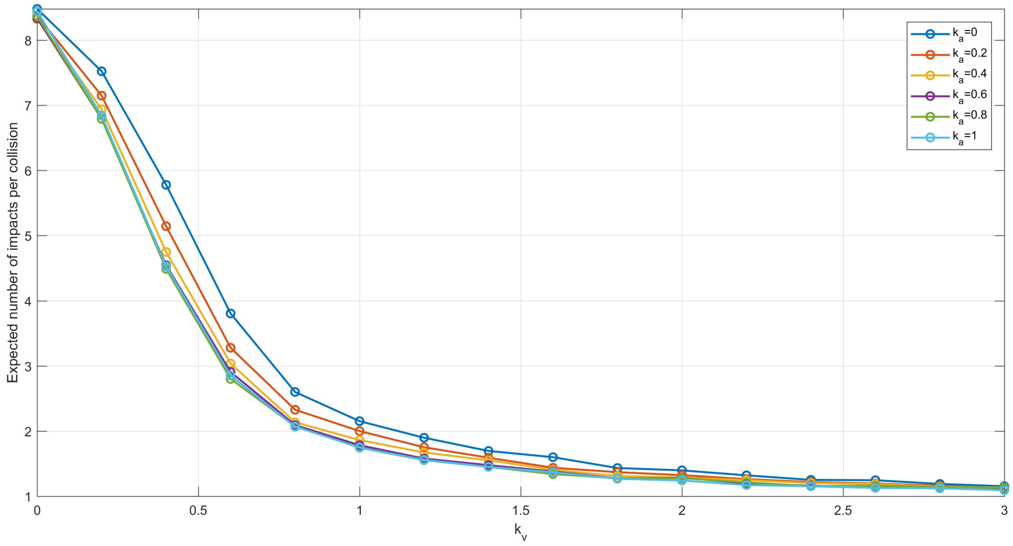

Figure 3.35: Expected number of impacts per collision with different k_v

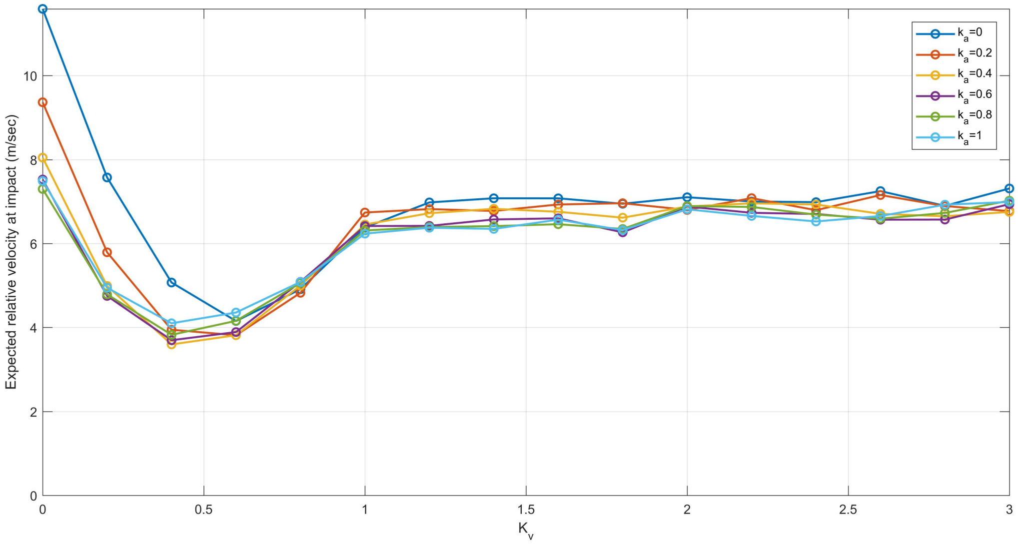

Figure 3.36: Expected velocity at impact with different k_v

3.6.3 Safety Set

Gains' effects on safety are complicated, and it's difficult to understand in an intuitive way. To have a clearer view, we plot safety sets with some thresholds bellowing. The safety set is a set of (k_p, k_v, k_a) such that every element (k_p, k_v, k_a) in this set contributes to a probability of collision less than a constant. We plot safety sets corresponding to probability of collision less than 50%, probability of collision less than 20%, probability less than 10% and probability less than 5% in Figure 3.37, Figure 3.38, Figure 3.39 and Figure 3.40 respectively. Since the range of (k_p, k_v, k_a) we examine is considerable large, we change gains in a step of 1. Therefore, these safety sets are not accurate enough. They can be only used to analyze the shape of real safety set roughly.

To shorten computing time, we first examine every possible combination of k_p, k_v and k_a with a low accuracy (about $\pm 2\%$) to get the safety set corresponding to probability less than 50%. In other words, some combinations whose probabilities of collision are 52% may be included in the set and we also miss some combinations whose probabilities of collision are 48%. And based on the safety set corresponding to probability lees than 50%, we pick those combinations whose probabilities of collision are less than 20% to construct the safety set corresponding to probability less than 20%. Therefore, the accuracy of safety set corresponding to probability less than 20% is also 2%. Because the remaining safety sets we need to search is corresponding to probability of collision less than 10%, 5% and 3%, we increase accuracy of computation to 0.5% and reexamine the safety set corresponding to probability less than 10% to correct probability of collision of each combination. After that, we select proper combinations for new safety set from it's parent set (the safety set corresponding to probability larger slightly) and repeat.

Comparing safety sets with different probabilities, we can find probability is quicker to respond to changing of k_v than k_a. And k_p and k_v in the safety set of least probability of collision are positive correlated.

If we examine the specific points in safety set for probability of collision less than 5%, we will find the least probability of collision that ACC can achieve is larger than that CACC can make. In other words, the best performance of ACC on probability of collision is worse than that of CACC, with the condition that (k_p, k_v, k_a) is in the range of $[0, 30] * [0, 30] * [0, 1]$.

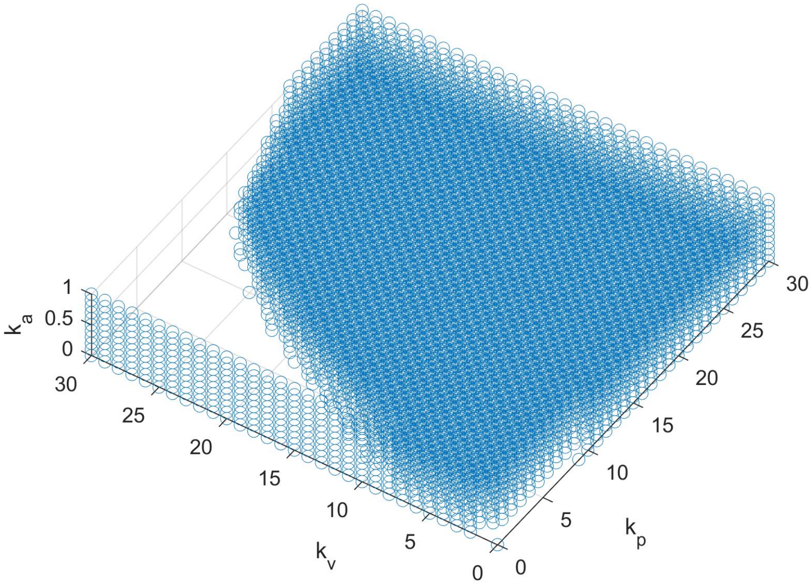

Figure 3.37: Safety set for probability of collision less than 50%

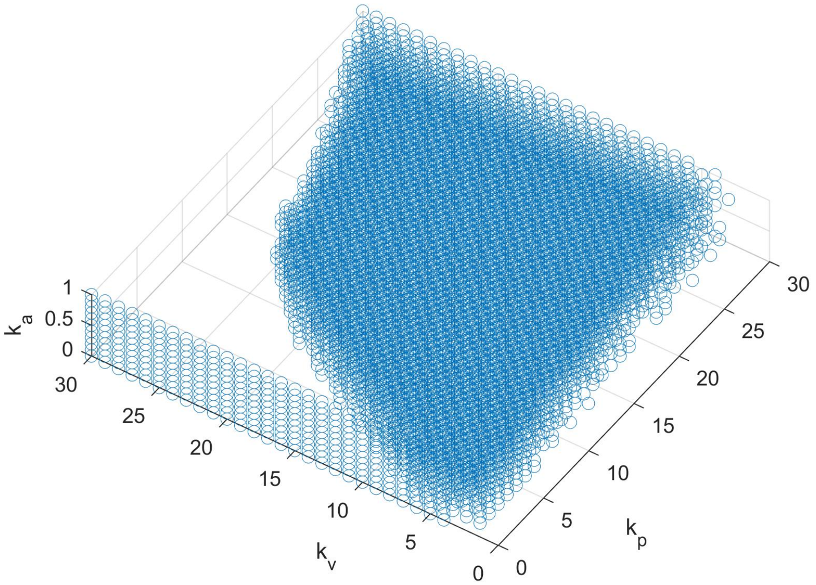

Figure 3.38: Safety set for probability of collision less than 20%

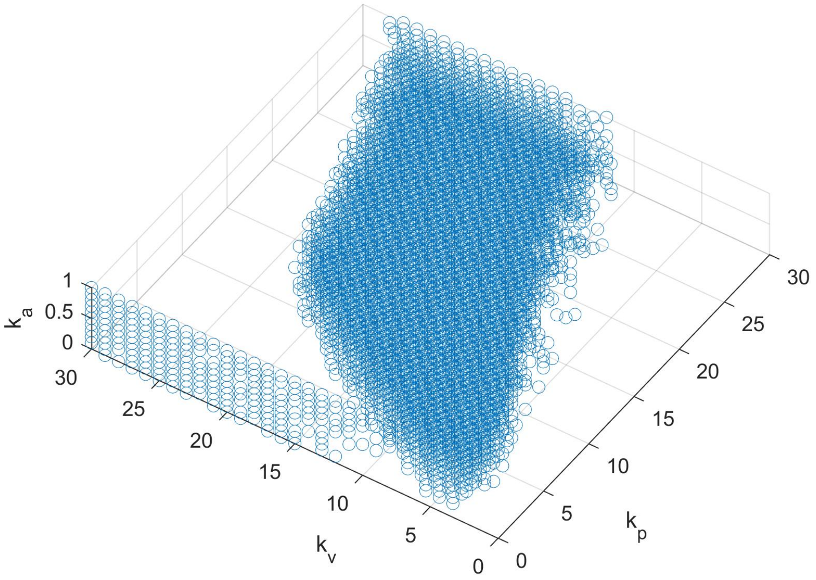

Figure 3.39: Safety set for probability of collision less than 10%

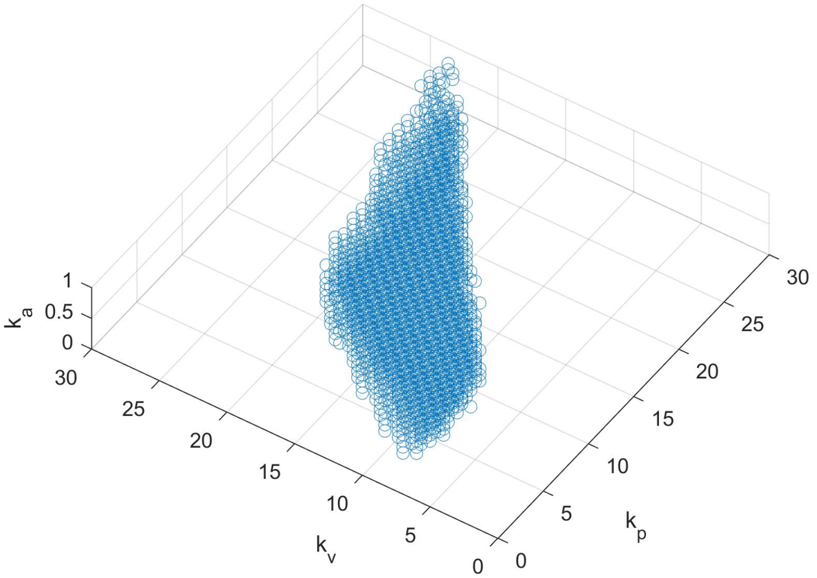

Figure 3.40: Safety set for probability of collision less than 5%

4. DISCUSSION

4.1 Different Criteria

Throughout the thesis, we have used four criteria - probability of collision, expected number of collisions, expected relative velocity at impact and variance of spacing error of third vehicle in the platoon, to decide which control strategy is better.

In most cases, these four criteria are consistent with each other. The probability of collision is not dependent on expected number of impacts and expected velocity at impact. For instance, when probabilities of collision of platoons with different sizes are identical in Figure 3.1, expected number of impacts and expected relative velocity at impact of platoons with different sizes vary a lot in Figure 3.2 and Figure 3.3. The expected relative velocity at impact is related to expected number of impacts per realization. As we discussed in the section about latency, an increase in expected relative velocity at impact may result from a reduction of expected number of impacts per realization. Note that crashes that happen in the tail of platoon are usually minor than crashes that happen at the front of platoon. So an increase in expected relative velocity at impact itself is not sufficient to say that safety is worse in this case. Variance of spacing error also has some properties that we can use to assess safety, such as its peak value, values at infinity, and the time when peak values appears. We could use values at infinity to estimate the probability collisions and peak values to estimate the severity of collision.

4.2 Parameter's Effect

Different parameters listed previously have different kinds of effects on different criteria. We summarize the results here.

Size of a platoon does not significantly affect the probability of a collision. But, an increment in the size of a platoon can increase the expected number of collisions and the expected relative velocity at impact.

Initial velocity has a significant influence on safety of CACC-equipped vehicle platoons. An increase in the initial velocity increases the probability of a collision, expected number of impacts and expected relative velocity at impact remarkably. Therefore, increment of velocity definitely worsen the safety of CACC.

An increase in parasitic latency increases the probability of a collision, expected number of both ACC-equipped and CACC-equipped vehicle platoons collision.

An increase in packet drop rate narrows the difference between CACC and ACC by raising probability of collision, expected number of impacts per collision and expected relative velocity at impact.

Length of vehicle behave like size of platoon. But length of vehicle does not only affect probability of collision, but also expected number of impacts per collision nor expected relative velocity at impact. In a word, length of vehicle doesn't affect safety of CACC at all.

Control gains affect safety of CACC and ACC in a complicated way. But in the range from 0 to 3 for both k_p and k_v, increments of k_p or k_v are eligible to improve the safety of CACC and ACC. Increase of k_p from 0 to 3 contributes to notable improvement of probability of collision for any k_a but no noticeable improvement of expected number of impacts per collision and expected relative velocity at impact when k_a is high. And increase of k_v from 0 to 3 is eligible to improve probability of collision and expected number of impacts per collision. The trend of expected relative velocity at impact with different k_v is affected by the number of impacts per collision.

These contribution from gains are only achieved in the certain range that we assume. When gains go to infinity, the platoon behaves in an uncoordinated way and the corresponding safety is much worse than the safety with respect to ACC or CACC.

4.3 ACC and CACC

With changing of k_a in assessments of various parameters, we can compare effects of CACC and ACC on the safety of platoon. With different parameters, k_a's effect on probability of collision, expected number of impacts per collision and expected relative velocity at impact varies a lot. In general, k_a contributes noticeable improvement on reductions of probability of collision and expected number of impact per collision regardless of changing of any kinds of parameters. And in most cases, k_a doesn't affect expected relative velocity at impact. Therefore, with respect to our criteria, CACC does contribute an improvement on safety over ACC in spite of changes of parameters or gains.

4.4 Accuracy

Since computation costs a significant amount of time, our accuracy of computation is not high. Therefore, unignorable errors exist in every assessment and safety sets. If time permits, one can get more accurate results by the same method.

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