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Simulation Framework for Vehicle Platooning and Car-following Behaviors under Connected-Vehicle Environment

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Abstract

This paper studies the traffic assistance system consisting of different kinds of vehicles (manual, Adaptive Cruise Control (ACC) and Cooperative Adaptive Cruise Control (CACC) vehicle). By using the application programming interface in microscopic-traffic simulation, the aim that constructing simulation framework of CACC platoon is achieved. Maneuvers like forming, adjusting, splitting, dismissing and joining in a platoon are implemented under the simulation platform. Then a platoon with 6 CACC vehicles is simulated to examine the interactions in a platoon and how they react to shockwaves microscopically, which in turn verify the driver model partly. Finally different market penetration and platoon size of CACC are tested. Results illustrate the lane capacity increased significantly when market penetration of CACC vehicles added, however platoon size have little impact on traffic capacity. These preliminary working will be a foundation for our future work in this area.

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Keywords: CACC; longitudinal control; platoon simulation.

1. Introduction

In recent years, freeway capacity has become a constraint causing regular traffic jams whilst building of new transport infrastructures seems no longer an appropriate option. To relieve congestion, considerable researches in the area of ITS (Intelligent Transportation Systems) are therefore performed to get a more efficient lane usage to increase the capacity of the road network. Ways like automatic platooning in AHS (Automated Highway System) have been proposed allowing for very small time gaps while maintaining the same velocity level, which is the

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key to greater capacity. As a consequence, vehicle platooning mechanism in longitudinal direction is required in order to still guarantee safety.

Semi-/automatic vehicle platooning is proved to be an efficient and effective way which is with the development and application of wireless communication and intelligent information technology, thus attracts much attention recently. In the vehicle platooning, Adaptive Cruise Control (ACC) system controls the distance, relative velocity or more preferably time headway between preceding vehicles. Cooperative Adaptive Cruise Control (CACC) system, on the other hand, uses vehicle to vehicle communication to gather information of vehicles further in front [1]. In these ways vehicles can follow each other with a closer distance, thereby improving traffic flow capacity.

However, such systems need special infrastructure and dedicated lanes, or as study shows that the result would be effective only when the percentage of automated vehicles is sufficiently high [2], which seem unlikely achieving for the near future. Surely traffic system in reality consisting of platoons that mixed with automated and/or semi-automated vehicles (e.g. ACC/CACC) and manually driven vehicles will be seen before the fully automated vehicles running in the AHS.

Since experiments concerning such mixed traffic stream cannot be implemented (a large fleet of semi/automated vehicles remain unavailable yet), research involving these areas require the help of simulation [3, 4]. On one hand, the processes in traffic networks are too complex for an analytic investigation; on the other hand, field evaluations are highly sought, and test bed deployments often come with high development cost. Therefore, a simulation approach seems to be adequate for preliminary evaluation with the help of the traffic simulator, and traffic flow simulation makes it possible to conduct a full analysis on CACC applications which have not implemented in the real world yet [5].

The paper is structured as follows: Section II reviews the state of the knowledge regarding modelling and simulating with ACC and CACC. In section III the characteristics of manual, ACC-based and CACC vehicle driving and platoon is presented, as well as their representation in terms of microscopic traffic models. Accordingly we construct mixed traffic simulation framework in section IV. Simulation results and conclusions were described in section V and VI, respectively.

2. Research Review

In the literature, it is well supplied with researches that attempt to introduce ACC or CACC into traffic stream. The effects of those driver assistance systems on the traffic dynamics have been usually addressed by means of traffic simulation because large-scale field experiments are scarcely possible with the existing conditions.

In 2001, VanderWerf at el. gave an overview about the effects that the introduction of ACC vehicles in the traffic stream will have on overall traffic behaviour (such as congestion, delay, safety, etc.), and they developed ACC and CACC mathematical model respectively [6]. A year later they used these models to simulate these three classes of vehicles and to estimate of highway capacity for different combinations of market penetration of ACC and CACC mixed with manually driven vehicles [2]. They used real-time information exchange of speed, acceleration and ACC status conditions of a similarly equipped preceding vehicle to make a CACC system. Thus it is able to follow at a much shorter headway of 0.5s and was also assumed not require any drive’s intervention.

Kesting et al. proposed a new car-following model that serves as the basis of an ACC implementation in real cars. The model is based on the intelligent driver model (IDM) and inherits its intuitive behavioural parameters:

desired velocity, acceleration, comfortable deceleration and desired minimum time headway, etc. His another paper shows that traffic congestion in the reference scenario was completely eliminated when simulating a proportion of 25% ACC vehicles, travel times were already significantly reduced for much lower penetration rates [7, 8].

Shladover and Nowakowski, at el. use field tests of ACC/CACC driven by 16 drivers who were encouraged to select the time gap settings that they preferred for each system [9,10], and results indicate the relative preferences for driving at the different available time gap settings. Based on this, Shladover at el. use traffic microsimulation with varying market penetrations of ACC/CACC, at their following work [11], to estimate the impacts on freeway capacity. Simulation results show that ACC is unlikely to produce any significant change in the capacity of freeway. CACC, in contrast, has the potential to substantially increase freeway capacity when it reaches a moderate to high market penetration owed to its shorter gap settings.

Arem at el. proposed Cooperative Following (CF) model using automated longitudinal control combined with intervehicle communication [12, 13]. It allows for anticipation to severe braking maneuvers in emerging shock waves with the aim of smoothening traffic flow and enhancing traffic safety. The functionality of CF has been modelled in the microscopic-traffic simulation model MIXIC, and the simulation has been run with a platoon of mixed CF equipped and nonequipped vehicles.

Sinan et al. thought that controlling over a wireless communication network is the enabling technology which makes CACC realizable. By studying the effects of wireless communication on the performance of an existing CACC controller they emphasize the necessity for considering CACC in a networked control system (NCS) framework [14].

In conclusion, more attentions in the literature are paid to the effects on traffic stream with the ACC and CACC, comparing with manual vehicle and about their market penetration analyzed in simulation. It seldom has a study on a very mixed simulation model, which manual vehicle, ACC and CACC coexist, to study various levels of platoon changes that could have effects on the traffic characteristic macroscopically. Besides, its lack of the elaboration of the micro behaviour characteristics should also be highlighted. Those hence are the main objective of this paper.

3. Vehicle Platoon and Modeling

In this paper, three types of vehicles including ACC, CACC and manually driven vehicle coexist in the freeway system, seeing Fig.1, and they can composite three different operation modes: a). common manual vehicle driving; b). single ACC or CACC vehicle driving; and c). CACC platoon driving. Here, we provide explanations of the last two ones below:

ACC—a system that automatically controls the gap between vehicles driving at freeway speeds based on measurements of the distance to the preceding vehicle [10], we assume that a CACC vehicle without adjacent one around maneuvers the same as ACC vehicle and will not be specially discussed in the following parts.

CACC—an enhancement to ACC that enables more accurate gap control and operations at smaller gaps (TC0, shown in Fig.1) by adding communication of vehicle status information (primarily speed and acceleration) from the preceding vehicle. More than 2 CACC vehicles nearby which has similar destination can constitute a platoon. Once CACC vehicles come to an agreement that they want to be a platoon, the first CACC vehicle in a group acts as a leader to dictate laws (called the Leader Law) about how to maneuver sequences of motions, and then the entire member CACC vehicle should obey.

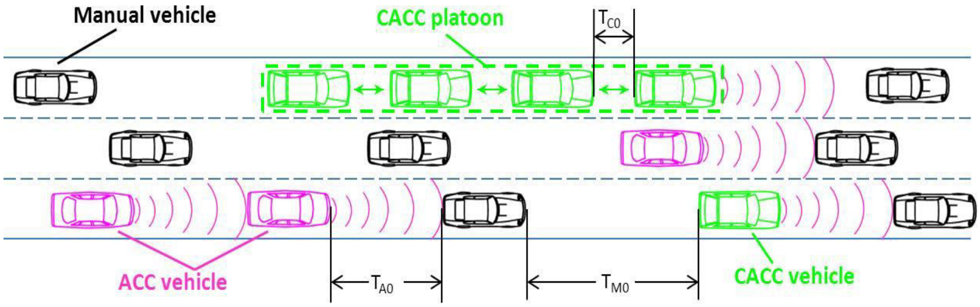

Fig.1. Three operation modes coexist in mixed freeway system

Above all, the characteristics of these three operation modes are shown as follows:

a) The finite reaction time of humans results in a delayed response to the traffic situation, which means it needs a long time gap TM0 (Fig.1) to follow the front vehicle;

b) Human drivers as well as CACC equipment could scan the traffic situation several vehicles ahead while ACC sensors are restricted to the vehicle immediately in front;

c) Several ACC vehicles can also comprise a platoon and it acts, however, the same as the single ACC vehicle because no information interchanges from the front ACC vehicle;

d) The communication between CACC vehicles in a platoon has different organization ways which could have influences on the traffic system.

3.1. CACC operation and modeling

More specifically, a platoon of CACC vehicles can be compared to a train, with the first vehicle of the platoon being the locomotive. Here we refer to the leader law which brings many benefits such as relieving the driving load of the following members and so forth. Vehicles equipped with CACC system have all the same capabilities. For safety reasons, however, we assume that only the authorized vehicle (which the model randomly choose and authorize the ability to group a platoon) can be the leader of the platoon. Each objected vehicle in the string has a preceding vehicle and a behind vehicle, and one possibly plays other roles in another ternate of vehicles as can be seen in Fig.2 (e.g., the forth vehicle follows the third but leads the fifth). The number of vehicles in the platoon is allowed to change as vehicles join in and split from the platoon, with assuming that the joining in maneuver can only happen in the rear of the platoon to be the newly rear vehicle while splitting maneuver is allowed anywhere of the platoon, and it is also the same for one platoon joining in or splitting from another [15].

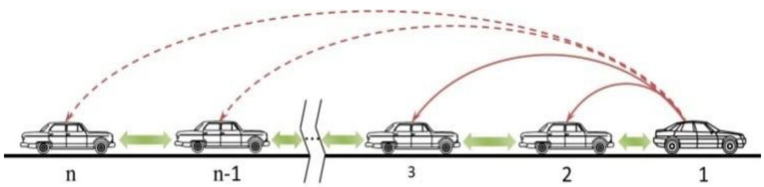

Fig.2. CACC leader control law

In the platoon operating, the leader may dictate action sequences that should be followed by the member vehicles. For example, when the leader dictates to perform acceleration or deceleration maneuver with no time delay, all the vehicles will simultaneously implement with the same acceleration/ deceleration at any given time. Some typical maneuvers for longitudinal (and lateral) controls in a platoon are join, split, entry, exit, etc.

In this section, the driver behaviour model from Wiedemann [16] is used, the basic idea of which assumes that a driver can be in one of the four driving modes: a) free driving, b) approaching, c) car-following and d) braking. For each mode, the acceleration is described as a result of speed, speed difference, distance and the individual characteristics of driver and vehicle. The driver switches from one mode to another as soon as he reaches a certain threshold that can be expressed as a combination of speed difference and distance.

Referring to CACC, these states would be detected and executed by the leader. Since approaching and braking are determined by model accelerations, and the free driving state attempts to maintain a desired velocity, we assume that these are achieved by the VISSIM simulator itself which will not be addressed here. Among the four states, car-following (the driver adjusts his speed and/or following distance with respect to traffic ahead) model is a key point. Vehicles driven by normal human are represented using a state-of-the-art model of car-following behaviour, here deriving from the psychological-physiological Widenmann 99 [16]. Some important parameters are explained here:

CC0 (Standstill distance): defines the desired distance between stopped cars. It has no variation; and,

CC1 (Headway time): is the time (s) that a driver wants to keep. The higher the value, the more cautious the driver is. Thus, at a given speed v (m/s), the safety distance dx_safe is computed to:

$$dx\_safe = CC0 + CC1 * v \tag{1}$$

The safety distance is defined in the model as the minimum distance a driver will keep while following another car. In case of high volumes this distance becomes the value with the strongest influence on capacity.

We selected ACC/CACC driving models from the literature and settled on [8], which using the driver-desired constant time-gap td between vehicles in a platoon to control ACC and CACC vehicles (for ACC, td was set 1.4s and 0.5s for CACC). The acceleration in those models is a linear of the current space s between the objective vehicle and its preceding vehicle and the current speed v of the objective vehicle, with which is limited into maximum and minimum accelerations. The accelerations of vehicles in next step are expressed by formula (2) and (3) for ACC vehicle:

$$a_c = k_v*(v_p - v_f) + k_s*(s - v*t_d) \tag{2}$$

$$a = max[a_{min}, min(a_c, a_{max})] \tag{3}$$

And (4) and (5) for CACC vehicle:

$$a_c = a_p + k_v*(v_p - v_f) + k_s*(s - v*t_d) \tag{4}$$

$$a = max[a_{min}, min(a_c, a_{max})] \tag{5}$$

Where:

a_c - control acceleration with the liner function;

a - acceleration in next step of the objective vehicle;
a_p - acceleration of the preceding vehicle;
v_p - speed of the preceding vehicle;
v_f - speed of the following vehicle;
a_{max} - maximum allowed acceleration;
a_{min} - maximum allowed deceleration ;
k_v, k_s - constant gains, both greater than zero.

3.2. Architecture of the Framework

For the model of CACC coexisted with ACC and manual vehicle, some gists require mentioning:

1) All member vehicles in the platoon are under the control of the leader vehicle in this paper, maneuvers like accelerating, keeping headway, lane changing are simultaneous. Besides, communication between two adjacent vehicles is engaged while separated ones cannot. Here “communication” refers to the degree of sharing operation parameters when simulation is carrying out. For instance, vehicle’s motion setting in this moment and next is determined by the leader as well as its neighbors;

2) The car-following gaps are self-adjusted dynamically. Once the leader exits, all the following member vehicles are dismissed;

3) The data structure of constructing a CACC platoon includes: lane number (where platoon located), platoon speed, the maximum and minimum time gap of car-following, platoon size (how many member vehicles in the platoon), ID of the leader and the tail vehicle, and the present position of the platoon;

4) The leader undertakes the mission of building a platoon, and it also requires informing its member vehicles parameters referring speed, lane, and platoon position and so on in each simulating step. These parameters represent the dictation of the next operation;

5) If a CACC vehicle applies to joining in a platoon, it seeks the nearest one and notifies the leader. The leader vehicle replies the joining vehicle and informs others about the following sequence operations via recalculating parameters. When a vehicle wants to split from the platoon, it applies to cancel the communication from the leader and turn to a free-control vehicle.

4. Simulation Construction

Because the classical traffic simulator cannot simulate operations of ACC and CACC, the mixed scenario was implemented as a C++ DLL (Dynamic Link Library) plug-in, which interfaces with the VISSIM external during the simulation. The DLL file works as an External Driver Behavior Model (EDBM), which can determine the next step maneuver-acceleration/deceleration, lane change, or the vehicle’s location and trajectory via calculating vehicle’s x-y axis.

The External Driver Model DLL Interface of VISSIM provides the option to replace the internal driving behaviour by a fully user-defined behaviour for some or all vehicles in a simulation run. The user-defined algorithm must be implemented in a DLL written in C/C++ which contains specific functions (as specified below). During a simulation run, VISSIM calls the DLL code for each affected vehicle in each simulation time step to determine the behaviour of the vehicle. VISSIM passes the current state of the vehicle and its surroundings to the DLL and the DLL computes the acceleration / deceleration of the vehicle and the lateral behaviour (mainly for lane changes) and passes the updated state of the vehicle back to VISSIM [17]. The simplified process can be seen in Fig.3.

The external driver model can be activated for each vehicle type separately by checking the checkbox “VISSIM/Base data/Vehicle Types/External Driver Model” and optionally a parameter file to be used. If this option is checked, the driving behaviour of all vehicles of this vehicle type will be calculated by the selected DLL. We will implement simulation scenario involving mixtures of controller types and quantity of vehicles in the next section.

5. Simulation Setup and Results

Manual vehicles, ACC equipped vehicles and platoons consisted with CACC vehicles are simulated on a 4 km stretch of road with a 2-lane freeway in the simulator VISSIM.

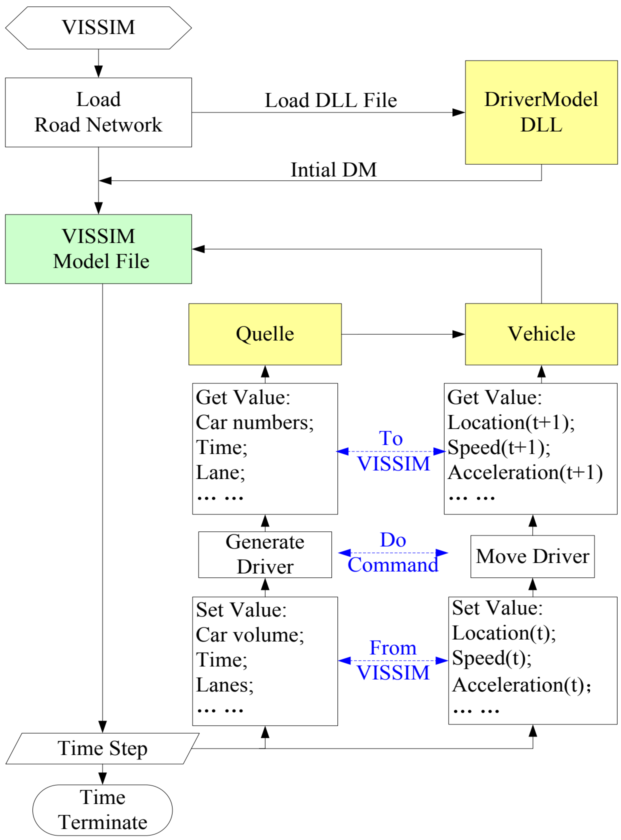

Fig.3. The diagram of interchanges between DriverModel DLL and VISSIM

5.1. Results of CACC Maneuvers

In the simulation, we use blue, white and red color to mark manual vehicle, ACC and CACC, respectively. The minimum desired headway of ACC in this paper is set 1.4s while 0.5s for CACC which derive from [13], the normal vehicle is based on VISSIM simulation itself. Some snapshots demonstrating CACC maneuvers within our simulation framework are given in Fig.4.

Fig.4 illustrates the simulation results for CACC maneuver which contains 6 vehicles. The CACC vehicles entered the simulation network randomly at the very beginning of the elapsed time[18] in snapshot a, and agree to constitute a platoon in snapshot b, then the leader dictate to all member vehicles to regulate their operation parameters and finish in snapshot c. At snapshot d, a CACC vehicle was permitted to join in the platoon then the platoon readjusted their headway in snapshot e. Snapshot f shows a member vehicle that was splitting the CACC, then the platoon readjusted soon afterwards in snapshot g. This CACC platoon was disassembled perhaps by a non-CACC vehicle broken in and made into 2 platoons in snapshot h.

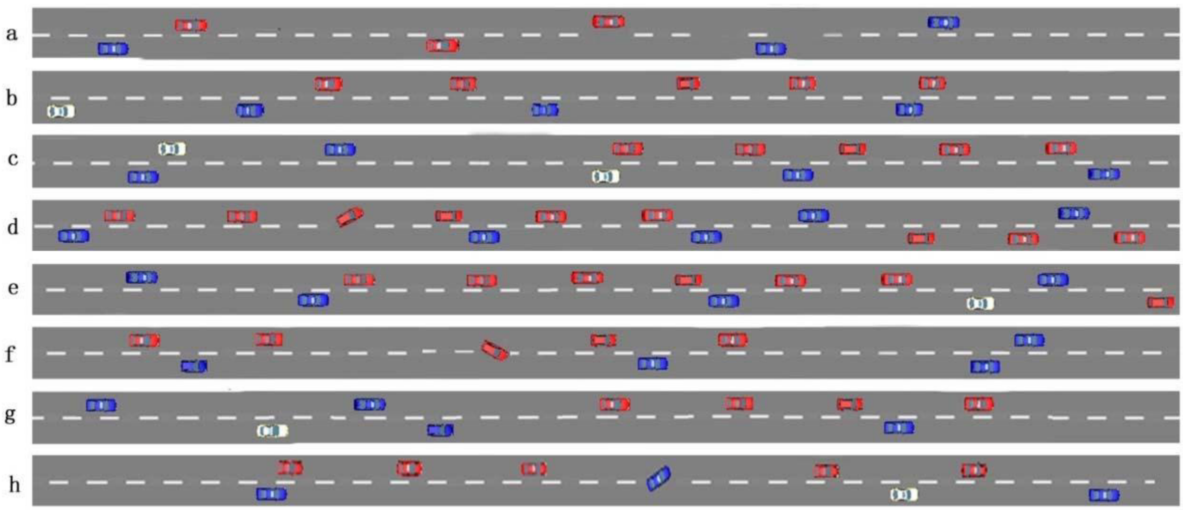

Fig.4. Simulation results of the CACC maneuvers

5.2. Simulation Data Output

In the simulation platform we built above, two experiments concerning platoon operation processes and the effects on traffic capacity were implemented. That is mainly to elaborate how CACC platoon works both in microscopic and macroscopic.

Firstly, we examined the operation of the CACC in microscopic, the time-gap setting of the CACC is set on td=0.5s between consecutive vehicles. The desired speed of CACC is set 80km/h and 6 CACC vehicles including the leader consist a platoon thus produce 5 gaps. The time gap and velocity data of each CACC vehicle is drawn in Fig.5.

CACC operation generally consists of three progresses: CACC forming, gap adjusting and platoon steadying. CACC vehicles enter into simulation system randomly then several CACC vehicles agree to constitute a platoon, then some adjustments such as following distance and platoon velocity.

After a period of time, CACC run into a relatively steady state with a platoon velocity (the platoon keeps desire velocity in Fig.5) and a minimum safe time gap. When confronting event, CACC produce requirement of speed down while all members act simultaneously, while the gap between two adjacent vehicles maintain unchanged (with subtle oscillations) as can be seen from Fig.5, thus illustrates that CACC platoon has a good stability dealing with shockwaves in simulation [19].

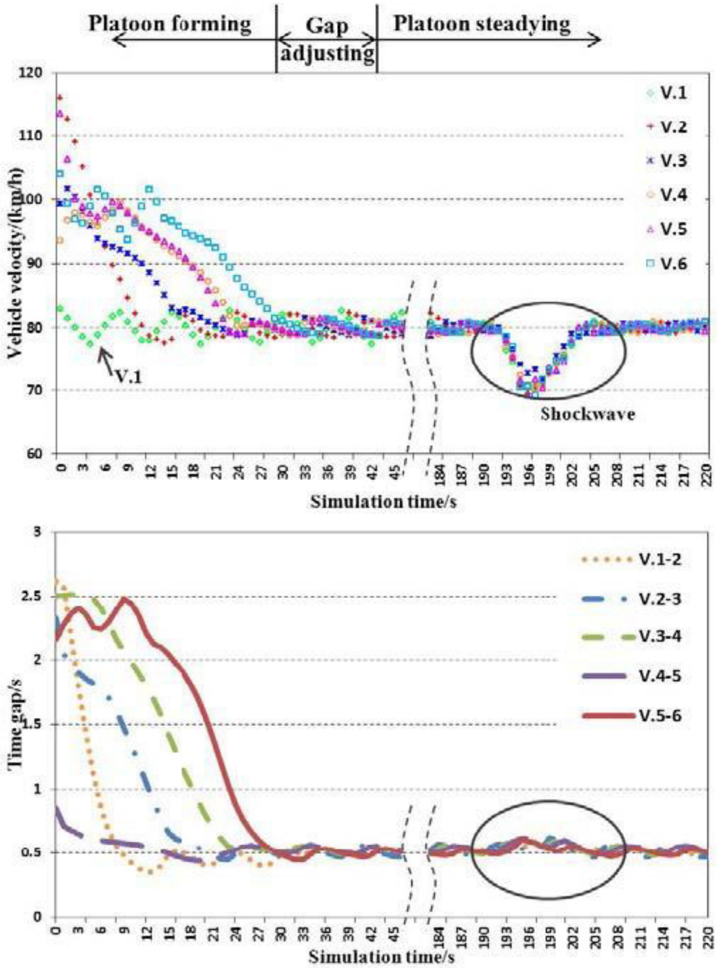

Fig.5. The velocity and time gap data of one CACC platoon, v.1 refers to leading vehicle and other member vehicles follow by number

With regard to how the market penetration of CACC affects traffic capacity. Since the platoon size would vary even in the same market penetration level, thereby it is also considered as a variable in the simulation experiments.

In the following test, the penetration rate of CACC vehicles varies from 10% to 100% in multiples 10%. Meanwhile, platoon size varies from 1 to 10 in multiples 1. Here we assume that ACC vehicles remain unchanged which account for 10%, then manual vehicle changes with the proportion of CACC market penetration. The desired speed of CACC is set 80km/h which is consistent with the situation in China freeway. To ensure statistical validity, 5 stochastically independent simulations were performed for each selected scenario. The result output can be seen in Fig.6 (Red dots represent the capacity value in each test).

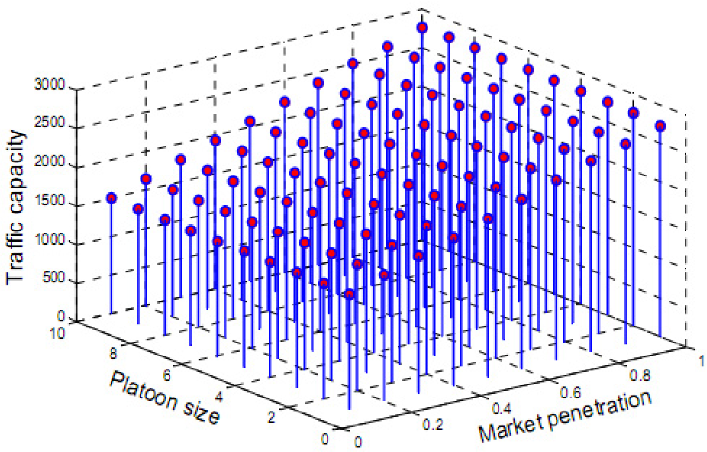

Fig.6. CACC on the impact of traffic capacity

Fig.6 demonstrates the traffic capacity increase significantly along with the CACC proportion increased however is barely affected by platoon size even though it dose increase when platoon size becomes large. That in other word means little additional advantage is gained by constituting a big CACC platoon, and the larger platoon might reduce flow when takes lateral maneuvers into consideration. Note that a platoon size of 1 functions as ACC (see Fig. 1), which will also have a positive effect on the increasing of the traffic capacity, with an increasing market penetration.

6. Conclusions and Future Works

In this article, we use the application programming interface of microscopic-traffic simulation Driver Model DLL. The aim is to construct the CACC simulation framework in a traffic assistance system consisting of different kinds of vehicles. Such a simulation platform can achieve maneuvers like forming, adjusting, splitting, dismissing and joining in a platoon. Though its microscopic operation and the reaction of CACC with shockwaves on, the simulation framework was verified to some extent. With different CACC market penetration and platoon size, we macroscopically examined the effects of ACC and CACC on freeway capacity. The results in this paper have contributed to the understanding of the CACC maneuvers on traffic flow, which will better prepare for our future work in this area.

The simulations were based on the assumption that vehicles especially CACC do not implement a lateral (e.g. lane change) movement in the 2-lane network while simulating. Moreover, the model for the three types of vehicles in the traffic system are used without calibration and further research due to limitations of both capability and qualification at our present conditions. Thus, adding lane-change model to the framework and studying on its differences among ACC, CACC and manual vehicle to revise the simulation model are of interests for future work.

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