Impact of Cooperative Adaptive Cruise Control on a Multilane Highway under a Differentiated per-lane Speed Limit Policy

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ABSTRACT

Cooperative Adaptive Cruise Control (CACC) has drawn wide attention in recent years for its potential throughput benefit, as it is a promising intermediate technology to the highly connected and automated vehicles. Existing literatures have well studied the impact of CACC on multilane highways, but they assumed under a uniform speed limit. Recently researchers revealed the traffic performs differently under a differentiated per-lane speed limit (DPLSL) policy with heavy vehicle (HV) restricted lanes. Whether the benefits of CACC still remain under a DPLSL policy has not been explored. Hence, this study developed cellular automaton models to incorporate CACC equipped and CACC non-equipped vehicles (i.e., passenger cars, HVs) on a two-way eight-lane highway with a DPLSL. Results shown throughputs by lane increase up to 78.5% as the CACC car market penetration rate (MPR) rises. Such increases became shaper (i.e., ≥10%) for inner lanes (i.e., HV restricted lanes) and outer lanes after reaching a 40% and a 60% CACC car MPR, seperately. Moreover, heavy vehicles induced a 1.5%~15.7% throughput reduction across lanes even under higher CACC car MPRs (i.e., 60%, 80%). Its traffic management strategy - DPLSL policy - may make the lanes experience a capacity penalty when their adjacent to another lane with a different speed limit. Lastly, in a traffic with a 60% CACC car MPR, increases are brought further by considering 10% of HV in CACC, especially on those HV non-restricted lanes. The study is helpful for policy makers to further prepare for the CACC’s prevalence in the forthcoming years.

Keywords: Cooperative Adaptive Cruise Control; Heavy Vehicle; Differentiated Per-lane Speed Limit; Multilane highways
INTRODUCTION

Efforts in intelligent transportation system (ITS) have been recently focused on the connected vehicles and automated vehicles. The former has been regarded as the key for ITS since it can integrate the vehicles, the infrastructure and other relevant elements together and the latter is attractive to the public for peoples’ expectation to free themselves from the driving tasks. The combination of the two (connected and automated vehicle, CAV) is widely believed to be the solution of the pain points in the current transportation system by making it safer, cleaner and smoother. Although it’s still a long way to go before the mass market has a full trust in the capability of high-level CAVs and gain full access to them, researchers started to study the traffic estimation and management using information at a low CAV market penetration rate (MPR). He et al. (1) estimated traffic speed using data collected by CAVs at a low MPR from 1% to 10%. Guo et al. (2) envisioned how freeway managed lane system changed in terms of mobility performance with the implementation of connected vehicle technology from a 10% MPR to higher. Meanwhile, the consecutive development of communication technology and computer science has made it possible for people to enjoy some intermediate technologies such as adaptive cruise control (ACC) and cooperative adaptive cruise control (CACC). ACC, as a driving assistance system, allows a vehicle to keep a specific headway desired by the driver with its immediately preceding vehicle while travelling and also to adjust accordingly. CACC is the prototype of CAV, which combines ACC with vehicle-to-vehicle (V2V) communication technology. Compared to ACC, CACC can provide “tighter vehicle following control” and “enhanced traffic flow stability” (3). Moreover, because vehicles can travel with a much shorter headway with its adjacent vehicles under CACC control than that under ACC, the highway capacity will also have further increase (4).

The mileage of newly built two-way eight-lane highways and those expanded from two-way four-lane highways in countries such as China has increased to meet the continuous growth of passenger and freight traffic in recent years. Compared to the conventional two-way four-lane highways, the extra lanes and the implementation of lane management measures has brought new changes to the traffic flow characteristic. In the two-way eight-lane case, the extra two lanes will provide the drivers on the middle two lanes with more than one choice in the lane changing process. Moreover, two-way eight-lane highway is often accompanied with speed control or lane control measures, such as the differentiated per-lane speed limit (DPLSL) policy. DPLSL is a frequently used speed control measure in countries like China and Thailand out of the traffic safety concern and is widely discussed recently (5–7). Under the DPLSL policy, the maximum speed limit and the minimum speed limit in each lane can be different, which influence the driver’s lane-changing behavior and makes the traffic flow on two-way eight-lane highways exhibits more complex features.

Great efforts have been made in the field of CACC modeling recently. Ye and Yamamoto (8) improved a two-state safe-speed model to better describe the motion of CACC vehicles by adopting additional constraints on a two-lane highway and found that when the CACC MPRs exceeded 30%, the road capacity would increase significantly, almost two times in the case where the desired time headway was set to be 0.5s. Talebpour and Mahmassani (9) established an integrated model that combined the following models of manual vehicles, connected manual vehicles and connected CAVs together, where the Intelligent Driver Model (IDM) was adopted for the simulation of CAVs. All their simulations were performed on a one-lane highway with an on-ramp located in the middle of the segment. Li et al. (10, 11) also used IDM to depict the
motion pattern of ACC and CACC vehicles and evaluate their possible effect on traffic safety. But Milanés and Shladover (12) doubted that the results of CACC simulation obtained from IDM were consistent with the actual case. They further proposed a new car following model for CACC vehicles which was validated by the real world CACC vehicle trajectory data and is employed by many researchers later. A recent Federal Highway Administration report (13) investigated the impact of automated truck platooning and found that activating truck platooning can lead to higher traffic throughput. Some researchers also started to evaluate the impact of road management policies with the presence of CACC vehicles in the transportation system. Under this case, the simulation scene has switched from single lane roadway to multi-lane highways since it’s the prerequisite for the implementation of road management measures. Liu et al. (14) investigated the impact of CACC dedicated lane on four-lane freeway segment and found that it contributed to the formation of CACC platoons, made the traffic flow more stable and the CACC vehicles more consistently distributed, thus increasing the overall roadway capacity.

Despite the fact that there has been plenty of works evaluating the impact of CACC vehicles on multilane highways, they all assumed that every lane had a uniform speed limit. Further, due to the nature of a multilane highway with the DPLSL policy, such highway segment restricts heavy vehicles travelling on inner lane(s). That is, when considering a 100% CACC MPR on passenger cars, the inner lane(s) is/are CACC dedicated. Although some studies have evaluated the impact of CACC dedicated lanes or impact of CACC vehicles on multilane highway, under the DPLSL policy and with the heavy vehicle (HV) restriction on inner lane(s), CACC vehicles are more likely to operate on inner lanes which may indicate different impacts compared with the previous studies.

In this study, the cellular automaton (CA) model is used to simulate the driving environment, since it is a widely employed method (15) in modeling the dynamic traffic system at a microscopic level. It is commonly considered in the existing studies, due to its high computational efficiency in simulating complex traffic systems. In a CA model, the simulated road segment consists of a series of consecutive cells and each of them is either empty or occupied by a vehicle. CA model applies fairly straightforward rules to reflect complicated vehicle behaviors and vehicle interactions in the real world. By incorporating forwarding rules, the vehicle can move from one cell to a downstream one or stop at each update interval and the adoption of specific lane-changing rules makes it possible to simulate the vehicular traffic in a multi-lane scene. The first CA model describing the motion of traffic flow was proposed by Nagel and Schreckenberg (16) in 1992. Knospe et al. (17) in 2000, introduced the variable brake light status to the model to reflect the fact that the drivers’ behavior was influenced by the preceding vehicles. It was further improved by Jiang and Wu (18), which is known as modified comfortable driving (MCD) model and can describe the synchronized flow well. Tian et al. (19) well replicated the phase transitions of traffic flow by introducing a safe-speed to the original model. Due to the model’s simplicity, high computational efficiency and capability to capture the characteristics of real traffic, it is also applied in other complex scenarios like work zone (20–22) and pedestrian flow (23–25). Recently, the CA models (26–32) have been used to simulate the heterogeneous traffic of human-driven vehicles and CACC vehicles. Ye and Yamamoto (26) constructed a CA model for both human driving vehicles and CACC vehicles and evaluated the impact of CACC vehicles on traffic safety. Their simulation site was on a 10 km two-lane roadway segment. Zhu et al. (27) proposed a four-lane CA model while considering the difference between the character of connected vehicle drivers and human driven vehicle drivers.
Hence, the authors explore whether the throughput benefits of CACC still stand under a more complex condition (i.e., a DPLSL policy with restricted HV lanes) using a CA model. This study incorporated CACC equipped passenger cars (CACC cars), CACC non-equipped passenger cars (non-CACC cars), CACC equipped heavy vehicles (CACC HVs) and non-CACC heavy vehicles (non-CACC HVs) under the DPLSL policy. For non-CACC cars and non-CACC HVs, the simulation framework is largely based on the Modified Comfortable Driving (MCD) model. Additional rules for HVs are considered so that the description of the influence of HVs is more natural and closer to the actual situation. For CACC cars and CACC HVs, the model adopted in this paper is based on the CACC car following model derived from the field CACC tests.

MODEL FRAMEWORK

The model framework introduces the vehicle types and their composition in the simulation network, provides the models describing the behavior of each vehicle type and explains the improved lane-changing model in detail.

Vehicle Types and Composition

In this paper, the total number of vehicles are divided into two categories—passenger cars and HVs. Passenger cars are further divided into CACC equipped passenger cars and non-CACC cars. For HVs, both CACC HVs and non-CACC HVs are considered. The vehicle composition of this study is illustrated in Figure 1.

The model is initialized to guarantee that the proportions of different vehicles on lanes with the same road management measures are identical. Firstly, passenger cars and HVs are divided based on vehicle types. HVs are not allowed to be driven on HV restricted lanes. CACC cars and non-CACC cars are divided into each lane according to the MPR of CACC cars. Since the main purpose of this study is to investigate whether the impact of CACC car still exists in DPLSL policy, the authors first evaluate throughputs across CACC car MPRs (i.e., 0%, 20%, 40%, 60%, 80%, 100%) at a fixed heavy vehicle percentage (HVP) of 10%. Then, this study explores the impact of HVPs on throughputs by varying it along with CACC car MPRs. Lastly, the authors consider 10% of HV in CACC and observe the influence of CACC HVs on the throughputs.

![Figure 1. Vehicle composition with a heavy vehicle percentage (\(\alpha\)) and market penetration rates (\(r_1\) for passenger cars and \(r_2\) for heavy vehicles)](image-url)
In the CA model, the length of the cells is 1.0 m and the default update interval is 1.0 s. In this study, the update intervals for non-CACC cars and non-CACC HVs are set to be 1.0 s and the update intervals for CACC cars and CACC HVs are 0.1 s, which will be elaborated later. The update rules for each type of vehicles are shown in the following parts, which can be divided into forwarding rules and lane-changing rules. In each time step, all the vehicles on the road segment first make lane changes according to the lane-changing rules in parallel and then move forward according to the forwarding rules, which is shown in Figure 2 and elaborated in the following parts.

**Figure 2. Representation of the cellular automaton model (Unit: meter)**

**Human-driven/CACC Non-Equipped Passenger Cars (non-CACC Car)**

Modified Comfortable Driving (MCD) model \((17, 33)\) is adopted to describe the behavior of non-CACC cars since it considers the drivers’ reaction and can describe the traffic flow features well \((18)\). The detailed modeling steps are shown as follows:

**Cycle Acceleration**

If \(B_{n+1}(t) = 0 \) or \((d_n - L) \geq h\) and \(V_n(t) > 0\), then

\[
V_n(t + \Delta t) = \min\left[V_n(t) + a_1 \Delta t, V_{\text{max}}\right]
\]

(1)

If \(V_n(t) = 0\), then

\[
V_n(t + \Delta t) = \min\left[V_n(t) + a_2 \Delta t, V_{\text{max}}\right]
\]

(2)

Else

\[
V_n(t + \Delta t) = V_n(t)
\]

(3)

Here, \(V_n(t)\) denotes the speed of the \(n\)th vehicle at the time \(t\) and \(B_{n+1}(t)\) denotes the brake light status of the preceding vehicle at time \(t\). \(\Delta t\) is the time step. \(B_n(t) = 0\) if the brake light is off while \(B_n(t) = 1\) if it’s on. \(a_1\) and \(a_2\) denote the accelerations of the non-CACC cars with constraint \(a_1 \geq a_2\), which is adopted to describe the slow-to-start rule that the drivers of stopped cars are less sensitive than the drivers of moving cars. \(V_{\text{max}}\) is the maximum speed of the non-CACC cars. \(d_n\) denotes the space gap between the front bumpers of the vehicle \(n\) and its...
preceding vehicle and it is calculated as \( d_{n} = X_{n+1}(t) - X_{n}(t) \). \( h \) is the variable determining the range of interaction with the brake light which prevents drivers from reacting to the light of a preceding vehicle that is too far away (17). Existing studies (17, 34, 35) revealed that \( h \) corresponds to an estimated value of \( 6 \cdot V(t) \Delta t \).

**Cycle Deceleration**

\[
V_{n}(t + \Delta t) = \min \left[ V_{n}(t + \Delta t), \frac{d_{\text{anti}}}{\Delta t} \right] \\
d_{\text{anti}} = d_{n} - L + \max \left( V_{\text{anti}} \Delta t - \text{gap}_{\text{safety}}^*, 0 \right) \\
V_{\text{anti}} = \min \left( \frac{(d_{\text{lead}} - L)}{\Delta t}, V_{\text{lead}} + a \Delta t, V_{\text{max}} \right)
\]

Here, \( d_{\text{anti}} \) and \( V_{\text{anti}} \) denote the anticipated net space gap and the anticipated speed respectively. \( d_{\text{lead}} \) denotes the space gap between the front bumpers of the leading vehicle and the leading vehicle’s preceding vehicle and \( V_{\text{lead}} \) denotes the speed of the preceding vehicle. \( \text{gap}_{\text{safety}} \) is the safety space gap.

**Stochastic Deceleration**

If \( rand < P \), then

\[
V_{n}(t + \Delta t) = \max \left[ V_{n}(t + \Delta t) - b \Delta t, 0 \right]
\]

Where,

\[
b = \begin{cases} b_1 & \text{if } V_{n}(t + \Delta t) < \left\lfloor \frac{d_{\text{anti}}}{T} \right\rfloor \\ b_2 & \text{otherwise} \end{cases}
\]

\[
P[V_{n}(t), B_{n+1}(t), t_{c}, t_{st}, d_{n}, L, h] = \begin{cases} P_{b} : B_{n+1} = 1 & \text{and } (d_{n} - L) < h \\ P_{0} : V_{n} = 0 & \text{and } t_{st} \geq t_{c} \\ P_{d} : \text{else} \end{cases}
\]

Here, \( B \) denotes the deceleration of the non-CACC cars and \( b_1 \) is smaller than \( b_2 \) because when \( V_{n}(t + \Delta t) \geq \left\lfloor \frac{d_{\text{anti}}}{T} \right\rfloor \), the driver is considered to be under the defensive state and more likely to have a larger deceleration rate. \( t_{st} \) is the cumulative stop time and \( t_{c} \) is the threshold of the cumulative stop time when drivers’ response sensitivity changes. \( T \) is the effective safe time gap. \( P_{b}, P_{0} \) and \( P_{d} \) are the stochastic deceleration probability under three different cases.

**Brake Light and Cumulative Stop Time Updates**

If \( V_{n}(t + \Delta t) < V_{n}(t) \), then

\[
B_{n}(t + \Delta t) = 1
\]

If \( V_{n}(t + \Delta t) > V_{n}(t) \), then

\[
B_{n}(t + \Delta t) = 0
\]

Else

\[
B_{n+1}(t) = B_{n}(t)
\]
If $V_n(t+\Delta t)=0$, then
\[ t_{st} = t_{st} + \Delta t \] (13)
If $V_n(t+\Delta t) > 0$, then
\[ t_{st} = 0 \] (14)

**Position Updates**

\[ X_n(t+\Delta t) = X_n(t) + V_n(t+\Delta t)\Delta t \] (15)

**CACC Equipped Passenger Cars (CACC Cars)**

In this study, the operating states of CACC cars are divided into two cases. The first case is when the preceding vehicle of a CACC car is CACC non-equipped. Under these circumstances, the CACC car becomes the string leader and the ACC mode is on. The modeling of a CACC car under ACC mode is shown as follows (36, 37):

\[ a^0(t) = k_1 [d_n(t-\Delta t) - T_{CACC} V_n(t-\Delta t) - L] + k_2 [V_{\text{lead}}(t-\Delta t) - V_n(t-\Delta t)] \] (16)
\[ a = \min(a^0, a_{\text{max}}) \] (17)
\[ V_n(t) = \min[V_n(t-\Delta t) + a\Delta t, V_{\text{max}}, d_{\text{max}}] \] (18)

$a^0$ is the acceleration returned by an ACC controller and $T_{CACC}$ stands for the desired time gap of an ACC controller. The brake light status and position update for CACC vehicles are the same as those for non-CACC cars. $k_1$ and $k_2$ are the gains on both the positioning and speed errors respectively.

The second case is when the preceding vehicle of a CACC car is also CACC equipped. Under this circumstance, the CACC mode is on and the modeling of a CACC car under CACC mode is shown as follows (36, 37):

\[ V_n(t) = \min[V_n(t-\Delta t) + k_p e_k(t) + k_d e_k(t), V_{\text{max}}] \] (19)
\[ a_n(t) = [V_n(t) - V_n(t-\Delta t)] / \Delta t \] (20)
\[ e_k(t) = d_n(t-\Delta t) - L - V_n(t-\Delta t) T_{CACC} \] (21)
\[ \dot{e}_k(t) = V_{\text{lead}}(t-\Delta t) - V_n(t-\Delta t) - T_{CACC} a_n(t-\Delta t) \] (22)

Here, $k_p$ and $k_d$ are gains trying to adjust the time-gap error with respect to the preceding vehicle. $e_k(t)$ denotes the time-gap error. $T_{CACC}$ denotes the constant time gap under the CACC mode and $V_{\text{lead}}(t)$ denotes the speed of the preceding vehicle. $\Delta t$ is the time step. When the CACC string exceeds its maximum length, the immediate CACC car behind the string will become the string leader and the constant time gap $T_{CACC}$ is 2.0 s. According to the work of Liu et al. (37), it is appropriate for the maximum string length to be chosen as 10-20 and in our study, the authors choose 15 as the maximum string length, which is same as their work. For conventional CA model, the update interval is 1.0 second, which is an acceptable value for human reaction time. However, this update interval is too long for CACC vehicles considering both the safety and CACC capability. Thus, in this study, the states of human-driven vehicles are
updated for only 1 time in each time step, while the states of CACC cars are updated for 10 times in each time step, which corresponds to a 0.1 second update interval.

**Heavy Vehicles (HV)s**

For non-CACC HVs, the operating rules are largely the same as those of non-CACC cars and for CACC HVs, the operating rules are largely the same as those of CACC cars. However, additional rules for HVs are considered to reflect the difference between HVs and passenger cars:

- Difference in dynamic characters between these two types of vehicles - it can be fulfilled by assigning different values to parameters like maximum speed, maximum acceleration, the vehicle length, etc.
- Psychological and behavioral impact of HVs on non-CACC drivers - according to Kong et al. (38), the drivers of cars will deliberately keep a certain distance from the preceding vehicle if the preceding vehicle is a HV.

Thus, in this study, the \( \text{gap}_{\text{safety}} \) and stochastic deceleration probability for non-CACC cars will be multiplied by expansion coefficients if a non-CACC car’s preceding vehicle is a HV, which can be shown as follows:

\[
gap_{\text{safety}} = \eta_{\text{gap}} \cdot \text{gap}_{\text{safety}}
\]

\[
p = \eta_p \cdot p
\]

Here, \( \eta_{\text{gap}} \) and \( \eta_p \) are expansion coefficients of \( \text{gap}_{\text{safety}} \) and stochastic deceleration probability respectively. Kong (39) analyzed the impact of heavy vehicles to passenger cars based on the video data of Shanghai-Nanjing highway and categorized the car-following states into four types according to different follower-leader pair, which are car-car type, car-truck type, truck-car type and truck-truck type respectively. According to his work, \( \eta_{\text{gap}} \) is 2.4 and \( \eta_p \) is a value ranging from 3 to 4.5. So here \( \eta_p \) is set to be the average of 3 and 4.5, which is 3.75. Besides, for CACC HVs, the constant time gap of a string leader is 2.5 s and the maximum string length is 6 (40).

**Lane Changing Behavior**

The lane changing model adopted in this study consists of two parts—the lane changing motivation and the safety criterion, which is shown as follows:

**Lane Changing Motivation**

\[
d_{\text{net}} < \min \left[ V_n(t) + a_n(t) \Delta t, V_{\text{max}} \right] \Delta t + \text{gap}_{\text{safety}}
\]

\[
d_{\text{net}} \geq \min \left[ V_n(t) + a_n(t) \Delta t, V_{\text{max}} \right] \Delta t + \text{gap}_{\text{safety}}
\]

\( d_{\text{net}} \) denotes the net space gap between current vehicle and its preceding vehicle in the current lane while \( d_{\text{net}} \) denotes the net space gap between current vehicle and its immediate ahead vehicle in the target lane. The criteria above describe the situation in which the current vehicle can achieve a higher speed or a better driving condition by lane changing.
Safety Criterion

\[ d_{\text{net}}^{\text{back}} \geq V_{\text{max}} \Delta t \] (27)

\( d_{\text{net}}^{\text{back}} \) denotes the net space gap between current vehicle and its immediate behind vehicle in the target lane.

When the above two criteria are met, the vehicle will change to the target lane with a certain probability. To further simulate the impact of HVs on non-CACC cars, the \( \text{gap}_{\text{safety}} \) and lane changing probability for non-CACC cars will also be multiplied by expansion coefficients if a non-CACC car’s preceding vehicle is a HV, which can be shown as follows:

\[ \text{gap}_{\text{safety}}' = \eta_{\text{gap}} \text{gap}_{\text{safety}} \] (28)

\[ P_{\text{LC}}' = \eta_{\text{LC}} P_{\text{LC}} \] (29)

Here, \( \eta_{\text{LC}} \) is the expansion coefficient of lane changing probability. \( P_{\text{LC}} \) and \( P_{\text{LC}}' \) are the lane change probability and the expanded lane changing probability respectively. Here, \( \eta_{\text{gap}} \) is set to be the same as that in equation 25 and according to Kong’s work (39), \( \eta_{\text{LC}} \) is set to be 1.25.

MODEL VALIDATION

In this study, the simulation site is based on a two-way eight-lane highway segment of Shanghai-Nanjing expressway, where the DPLSL is adopted to control the speed of vehicles on each lane. The study site is on main lanes with no on-ramps or off-ramps. The most inner lane and the second most inner lane are exclusively for passenger cars with a maximum speed limit of 120 km/h. The maximum speed limits for the most outer lane and the second most outer lane are all 100 km/h. HVs are only allowed to be driven on the most outer lane and the second most outer lane. In this study, the lanes in the same direction are defined as lane 1, lane 2, lane 3 and lane 4 from the inner to the outer.

The field data was collected in October, 2019, from a 4.5 km long highway segment of Shanghai-Nanjing expressway through microwave vehicle detectors and camera monitors. The microwave vehicle detectors collected traffic data (i.e., car-following percentage, average space gap, count of each vehicle type, and average speed of each vehicle type) in every 5 minutes. The preprocessing of the raw data from microwave vehicle detectors includes the deletion of outliers and data smoothing. A four-hour video was collected by camera monitors throughout three different days (i.e., holiday, weekday and weekend respectively).

For the non-CACC CA models, the variables are carefully calibrated to achieve a comparable result to the observed data by minimizing the relative error (i.e., less than 6%) between simulated and observed flow and speed. The result is shown in Table 1.

<table>
<thead>
<tr>
<th>Lane No.</th>
<th>Lane 1</th>
<th>Lane 2</th>
<th>Lane 3</th>
<th>Lane 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Observed (veh/h/ln)</td>
<td>1,356</td>
<td>1,296</td>
<td>1,242</td>
<td>816</td>
</tr>
<tr>
<td>Simulated (veh/h/ln)</td>
<td>1,378</td>
<td>1,242</td>
<td>1,213</td>
<td>784</td>
</tr>
<tr>
<td>Relative Error (%)</td>
<td>1.6%</td>
<td>4.2%</td>
<td>2.3%</td>
<td>3.9%</td>
</tr>
<tr>
<td>Average Speed</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Observed (km/h)</td>
<td>103.6</td>
<td>96.8</td>
<td>79.8</td>
<td>70.2</td>
</tr>
<tr>
<td>Simulated (km/h)</td>
<td>106.2</td>
<td>100.4</td>
<td>84.3</td>
<td>73.0</td>
</tr>
<tr>
<td>Relative Error (%)</td>
<td>2.5%</td>
<td>3.7%</td>
<td>5.6%</td>
<td>4.0%</td>
</tr>
</tbody>
</table>
In CA models, an 18.0 km long (18,000 cells) highway segment is constructed and the vehicle arriving rate and the vehicle composition are assumed to be the same as the collected data for 4.5 km segment. Because CACC is a long-distance travel capability, the evaluation of impact brought by CACC is more accurately at a longer segment. It is a valid assumption to keep collected vehicle arriving rate and the vehicle composition the same, considering the observed field data are from main lanes without on and/or off ramps. Then, with the CA models simulated on an 18.0 km segment, the non-CACC CA models are also extended to the same length.

In the simulation, three virtual flow detectors were set to record the vehicle speed and the traffic flow of the four lanes, as illustrated in Figure 3 below. The first 1200 iteration steps are considered as the warm-up time and the collection of the desired parameters starts after that. The throughput of the highway segment is defined as the maximum 15-minute average flow rate of the three virtual flow detectors. The simulation was started by setting a relative low traffic volume per hour at first and then a slightly incremental volume the next time until the throughput obtained no longer increased. For each case, the simulation was run with 5 different random seeds and the final throughput was calculated as the average of the value gained at the 5 times.

Figure 3. Simulation site of highway segment with differentiated per-lane speed limit and heavy vehicle restriction lanes

For the CACC CA model, since there is no empirical data to describe the behavior of CACC cars and CACC HVs, the variables related with dynamic characters are assumed to be the same as those of non-CACC cars and non-CACC HVs; whereas the CACC car following variables are set to be the same as the works of Milanés and Shladover (36), Liu et al. (37), Chen et al (40) and Ramezani et al (41). The variables for all CA models are in Table 2.
### Table 2. Variable Names and Values in Cellular Automaton Models

<table>
<thead>
<tr>
<th>Cellular Automaton Model</th>
<th>Variable Name</th>
<th>Variable</th>
<th>Value</th>
<th>Cell</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vehicle length of non-CACC car</td>
<td>$L_{\text{non-CACC}}$</td>
<td>5 m</td>
<td>5 cells</td>
<td>Assumed</td>
</tr>
<tr>
<td></td>
<td>Vehicle length of heavy vehicle</td>
<td>$L_{HV}$</td>
<td>12 m</td>
<td>12 cells</td>
<td>Calibrated</td>
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<tr>
<td></td>
<td>Maximum speed of non-CACC car</td>
<td>$V_{\text{max}}^{\text{non-CACC}}$</td>
<td>33 m/s</td>
<td>33 cells/s</td>
<td>Calibrated</td>
</tr>
<tr>
<td></td>
<td>Maximum speed of heavy vehicle</td>
<td>$V_{\text{max}}^{HV}$</td>
<td>28 m/s</td>
<td>28 cell/s</td>
<td>Calibrated</td>
</tr>
<tr>
<td></td>
<td>Maximum acceleration</td>
<td>$a_{\text{max}}$</td>
<td>3 m/s²</td>
<td>3 cells/s²</td>
<td>Calibrated</td>
</tr>
<tr>
<td></td>
<td>Acceleration of non-CACC car when $B_{n+1}(t) = 0 \quad \text{or} \quad (d_n - L) \geq h$ and $V_n(t) &gt; 0$</td>
<td>$a_{1,\text{non-CACC}}$</td>
<td>2 m/s²</td>
<td>2 cells/s²</td>
<td>Assumed</td>
</tr>
<tr>
<td></td>
<td>Acceleration of non-CACC car when $V_n(t) = 0$</td>
<td>$a_{2,\text{non-CACC}}$</td>
<td>1 m/s²</td>
<td>1 cells/s²</td>
<td>Assumed</td>
</tr>
<tr>
<td></td>
<td>Deceleration of non-CACC car when $V_n(t+\Delta t) &lt; [d_{\text{min}}/T]$</td>
<td>$b_{1,\text{non-CACC}}$</td>
<td>1 m/s²</td>
<td>1 cells/s²</td>
<td>Assumed</td>
</tr>
<tr>
<td></td>
<td>Deceleration of non-CACC car when $V_n(t+\Delta t) \geq [d_{\text{min}}/T]$</td>
<td>$b_{2,\text{non-CACC}}$</td>
<td>2 m/s²</td>
<td>2 cells/s²</td>
<td>Assumed</td>
</tr>
<tr>
<td></td>
<td>Acceleration of heavy vehicle when $B_{n+1}(t) = 0 \quad \text{or} \quad (d_n - L) \geq h$ and $V_n(t) &gt; 0$</td>
<td>$a_{1,HV}$</td>
<td>1 m/s²</td>
<td>1 cells/s²</td>
<td>Assumed</td>
</tr>
<tr>
<td></td>
<td>Acceleration of heavy vehicle when $V_n(t) = 0$</td>
<td>$a_{2,HV}$</td>
<td>1 m/s²</td>
<td>1 cells/s²</td>
<td>Assumed</td>
</tr>
<tr>
<td></td>
<td>Deceleration of heavy vehicle when $V_n(t+\Delta t) &lt; [d_{\text{min}}/T]$</td>
<td>$b_{1,HV}$</td>
<td>1 m/s²</td>
<td>1 cells/s²</td>
<td>Assumed</td>
</tr>
<tr>
<td></td>
<td>Deceleration of heavy vehicle when $V_n(t+\Delta t) \geq [d_{\text{min}}/T]$</td>
<td>$b_{2,HV}$</td>
<td>1 m/s²</td>
<td>1 cells/s²</td>
<td>Assumed</td>
</tr>
<tr>
<td></td>
<td>Effective safe time gap of heavy vehicle</td>
<td>$T_{HV}$</td>
<td>2.5 s</td>
<td></td>
<td>Assumed</td>
</tr>
<tr>
<td></td>
<td>Effective safe time gap of non-CACC car</td>
<td>$T_{\text{non-CACC}}$</td>
<td>1.8 s</td>
<td></td>
<td>Assumed</td>
</tr>
<tr>
<td></td>
<td>Threshold of the cumulative stop time</td>
<td>$t_c$</td>
<td>10 s</td>
<td></td>
<td>Calibrated</td>
</tr>
<tr>
<td></td>
<td>Safety space gap</td>
<td>$\text{gap}_{\text{safety}}$</td>
<td>7 m</td>
<td>7 cells</td>
<td>Calibrated</td>
</tr>
<tr>
<td></td>
<td>Lane-changing probability of non-CACC car</td>
<td>$P_{\text{LC}}^{\text{non-CACC}}$</td>
<td>0.50</td>
<td></td>
<td>Calibrated</td>
</tr>
<tr>
<td></td>
<td>( p^\text{HV} )</td>
<td>( p^\text{LC} )</td>
<td>( p )</td>
<td>( p_d )</td>
<td></td>
</tr>
<tr>
<td>--------------------------</td>
<td>-------------------</td>
<td>-------------------</td>
<td>-------</td>
<td>--------</td>
<td></td>
</tr>
<tr>
<td>Lane-changing probability of heavy vehicle</td>
<td>0.35</td>
<td></td>
<td></td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Stochastic deceleration probability when ( B_{n+1} = 1 \text{ and } (d_n - L) &lt; h )</td>
<td>0.32</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stochastic deceleration probability when ( V_n = 0 \text{ and } t \geq t_c )</td>
<td>0.14</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stochastic deceleration probability in other cases</td>
<td></td>
<td></td>
<td></td>
<td>0.05</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>( L^\text{Car}_{\text{CACC}} )</th>
<th>( \Delta t )</th>
<th>( k_1 )</th>
<th>( k_2 )</th>
<th>( k_p )</th>
<th>( k_d )</th>
<th>( T^\text{Car}_{\text{ACC}} )</th>
<th>( T^\text{Car}_{\text{CACC}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CACC passenger car</td>
<td>5 m</td>
<td>0.1 s(^{-1})</td>
<td>0.23 s(^{-2})</td>
<td>0.07 s(^{-1})</td>
<td>0.45 s(^{-1})</td>
<td>0.25</td>
<td>2 s</td>
<td>0.71 s</td>
</tr>
<tr>
<td>Gains on the positioning errors</td>
<td>( k_1 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Milanés and Shladover (36)</td>
<td></td>
</tr>
<tr>
<td>Gains on the speed errors</td>
<td>( k_2 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Liu et al. (37)</td>
<td></td>
</tr>
<tr>
<td>Gains for adjusting the time gap</td>
<td>( k_p )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gains for adjusting the time gap</td>
<td>( k_d )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Desired time gap of an ACC controller for passenger car</td>
<td>( T^\text{Car}_{\text{ACC}} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant time gap under the CACC mode for passenger car</td>
<td>( T^\text{Car}_{\text{CACC}} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>( L^\text{HV}_{\text{CACC}} )</th>
<th>( \Delta t )</th>
<th>( k_1 )</th>
<th>( k_2 )</th>
<th>( k_p )</th>
<th>( k_d )</th>
<th>( T^\text{HV}_{\text{ACC}} )</th>
<th>( T^\text{HV}_{\text{CACC}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CACC heavy vehicle</td>
<td>12 m</td>
<td>12 cells</td>
<td>0.0561 s(^{-2})</td>
<td>0.3393 s(^{-1})</td>
<td>0.45 s(^{-1})</td>
<td>0.25</td>
<td>2.5 s</td>
<td>1.5 s</td>
</tr>
<tr>
<td>Gains on the positioning errors</td>
<td>( k_1 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Ramezani (41)</td>
<td></td>
</tr>
<tr>
<td>Gains on the speed errors</td>
<td>( k_2 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Milanés and Shladover (36), Chen et al (40)</td>
<td></td>
</tr>
<tr>
<td>Gains for adjusting the time gap</td>
<td>( k_p )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gains for adjusting the time gap</td>
<td>( k_d )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Desired time gap of an ACC controller for heavy vehicle</td>
<td>( T^\text{HV}_{\text{ACC}} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant time gap under the CACC mode for heavy vehicle</td>
<td>( T^\text{HV}_{\text{CACC}} )</td>
<td></td>
<td></td>
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</tbody>
</table>
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1 RESULTS

In the following result section, the traffic performance (i.e., throughput) of the introduced eight-lane highway segment under DPLSL policy will be first evaluated in different CACC car MPRs (i.e., 0%, 20%, 40%, 60%, 80% and 100%) with a fixed 10% HVP. Then, the throughputs of the segment with 0%, 5% and 10% HVPs will be compared between two CACC MPRs (i.e., 60% and 80%) to understand the impact brought by HVs. Lastly, the authors consider 10% of HV in CACC and observe and evaluate the possible impact of heavy vehicle platooning on the throughputs.

Impact of CACC Car on a Multilane Highway with DPLSL Policy

A series of CACC car MPRs ranged from 0% to 100% with an incremental of 20% is implemented in the multilane highway system with a DPLSL policy at a fixed 10% HVP. Figure 4 shows the vehicle compositions from the simulation.

![Vehicle composition per lane at different CACC car market penetration rates](image)

**Figure 4. Vehicle composition per lane at different CACC car market penetration rates (MPR) with a 10% heavy vehicle percentage**

With the vehicle compositions above, throughputs at different CACC car MPRs are listed in Table 3 below. At each CACC car MPR, the throughput is larger in the inner lane and smaller in the outer lane considering the DPLSL policy provides different maximum and/or minimum speed limit per lane. Moreover, the overall trends of the throughputs consistently increase for all four lanes as the CACC car MPR increases. However, when the MPR is less than 40%, the increase in the throughput is relatively slow. The benefit of CACC is not obvious because there are only few CACC cars in the network. When the MPR exceeds 60%, the increase in throughput becomes sharp. For example, the increase in throughput is below 10% when CACC car MPR is at 20% and 40% for lane 1; greater increases (i.e., 18.7%, 43.6%, and 78.5%) are observed at a CACC car MPR of 60% and higher. Such observations agree with the findings from Liu et al. (42).
Table 3. Throughput at Different CACC car MPRs

<table>
<thead>
<tr>
<th>Lane No.*</th>
<th>HV Restricted? (Y/N)</th>
<th>Maximum Speed Limit (km/h)</th>
<th>Minimum Speed Limit (km/h)</th>
<th>Throughput at CACC MPRs (Throughput Percentage Difference**)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0%</td>
</tr>
<tr>
<td>1</td>
<td>Y</td>
<td>120</td>
<td>110</td>
<td>1,940 (na)</td>
</tr>
<tr>
<td>2</td>
<td>Y</td>
<td>120</td>
<td>90</td>
<td>1,836 (na)</td>
</tr>
<tr>
<td>3</td>
<td>N</td>
<td>100</td>
<td>80</td>
<td>1,796 (na)</td>
</tr>
<tr>
<td>4</td>
<td>N</td>
<td>100</td>
<td>60</td>
<td>1,786 (na)</td>
</tr>
</tbody>
</table>

* Lane number 1 indicates the most inner lane, and lane number 4 indicates the most outer lane.

** Throughput percentage difference is respect to 0% MPR; throughput percentage difference at 0% MPR is not applicable (na).

Moreover, from Figure 5, differences existed in the growth trends of throughput among the four lanes. Compared to the 0% CACC car MPR case, the throughputs of lane 1 and lane 2 can increase by 78.5% when the CACC car MPR is 100%, while the throughputs of lane 3 and lane 4 only increase by 46.9% and 44.7%. This indicates that under DPLSL policy, the inner lanes are more beneficial from CACC technology. At the same time, the restricted HV lanes create a dedicated or almost dedicated environment as MPRs exceeds 60%.

The throughput of lane 1 is the largest among all the four lanes under all CACC car MPRs, which is in line with our expectations. The throughput of lane 2 is always less than that of lane 1 and as the CACC car MPR rises, the gap between the two also becomes larger. The difference between the two lanes is interesting since the two lanes adopt the same road management policy. The reason can be that lane 2 is adjacent to lane 3 and is negatively affected by lane 3, which adopts a lower maximum speed limit and allows the entry of HVs. When vehicles from lane 3 switches to lane 2, they inevitably interfere the traffic flow on lane 2 because their speed is likely to be lower than that of lane 2 and the lane-changing behavior also brings interference, thus causing the reduction on the lane throughput.

Figure 5. Throughput of Each Lane under Different CACC MPR with a 10% heavy vehicle percentage
The gap between the throughputs of the four lanes are not obvious when the CACC car MPR is zero. When the MPR is 40%, the gap narrows down compared to the zero CACC MPR case and once the MPR is greater than 40%, it becomes larger ever since. This may be also because under a relatively low MPR, the benefit of CACC technology is not obvious. Despite the fact that the throughputs of lane 1 and lane 2 are always larger than those of lane 3 and lane 4, the gap between the throughputs of lane 3 and lane 4 is not evident compared to those of lane 1 and lane 2. That is because the traffic flow states in lanes 3 and 4 are similar since they are dominated by the presence of the heavy trucks. Under all the MPR cases, the throughput of lane 3 is only slightly larger than that of lane 4, which is reasonable since the two lanes adopt the same road management measures.

**Impact of Heavy Vehicle Percentages**

In order to figure out the impact of heavy vehicles, in this section, the simulation is conducted while the maximum speed limits and the CACC car MPR are holding still. Since the benefit of CACC technology appears after the CACC car MPR exceeds 40%, in this section, the experiments are conducted when CACC car MPR is fixed to be 60% and 80% respectively. For each experiment, the cases when the proportions of CACC non-equipped heavy vehicle are 0%, 5%, 10% are investigated. The vehicle composition per lane at different heavy vehicle percentages with 60% and 80% MPRs is shown in Figure 6. The results are shown in Figure 7 and Table 4. In Table 4, the theoretical capacity for conventional manual driving estimated from HCM 2010 is also provided. Lastly, as shown in the vehicle compositions in Figure 6, additional experiments are conducted in the 10% HVP with CACC equipped HVs to evaluate and compare their impact on throughputs. Results are in Table 5.

![Vehicle Composition Per Lane](image)

(a) Vehicle composition per lane with a 60% MPR

**Figure 6.** Vehicle composition per lane at different heavy vehicle percentages (HVPs) with a 60% and 80% CACC car market penetration rate
(b) Vehicle composition per lane with an 80% MPR

Figure 6. Vehicle composition per lane at different heavy vehicle percentages (HVPs) with a 60% and 80% CACC car market penetration rate (cont’d)

The overall trend of the throughput over HVP is that the throughput of each lane decreases as the HVP becomes larger for all the four lanes regardless of the CACC car MPRs. Under a 60% CACC car MPR, as the HVP rises from 0% to 10%, the throughput of lane 1 and lane 2 are decreased by 1.5% and 3.9% respectively while these of lane 3 and lane 4 are decreased by 5.0% and 8.1% respectively. Similar trend exists when the MPR is 80% that the reduction on the throughputs of lane 1 and lane 2 are less than these of lane 3 and lane 4. When the MPR is 80%, the reduction on the throughputs of lane 1 and lane 2 are 2.4% and 3.5% while the reduction on these of lane 3 and lane 4 are 7.8% and 15.7%. This shows that the influencing scope of HVs is mainly on the lanes they are allowed to be driven on. The reduction on the throughputs of lane 2 is slightly larger than those of lane 1, which is in consistency with our expectation that the traffic flow on lane 2 is more susceptible than lane 1.

Moreover, although the estimated theoretical capacity for conventional manual driving is not comparable with throughput outcomes from CA models, the throughput percentage differences are comparable. Seen from Table 4, the effects of HV are the same regardless of CACC car MPRs and are the same with HCM 2010. However, most of the percentage differences from CA models with CACC cars are smaller than those reported from HCM 2010 and the throughput reductions on lane 4 under an 80% MPR are very close to those reported from HCM 2010. On the whole, a larger negative effect of HV is observed at a larger CACC car MPR. For instance, the throughput percentage differences at 10% HVP are -1.5%, -3.9%, -5.0%, and -8.1% for each lane when CACC car MPR is 60%; meanwhile, these are -2.4%, -3.5%, -7.8% and -15.7% for each lane when CACC car MPR is 80%. Also, according to the HCM 2010, if there is no HV on the lane, then there will be no reduction on the theoretical capacity. However, there is actually reduction observed by CA model.
Table 4. Throughput at Different HVPs with a 60% and 80% CACC car MPRs

<table>
<thead>
<tr>
<th>Lane No.*</th>
<th>Lane 1</th>
<th>Lane 2</th>
<th>Lane 3</th>
<th>Lane 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Throughput</td>
<td>0% HVP</td>
<td>2,342 (na)</td>
<td>2,195 (na)</td>
<td>2,126 (na)</td>
</tr>
<tr>
<td>(Percentage Difference**)</td>
<td>5% HVP</td>
<td>2,324 (-0.8%)</td>
<td>2,138 (-2.6%)</td>
<td>2,046 (-3.8%)</td>
</tr>
<tr>
<td>MPR=60%</td>
<td>10% HVP</td>
<td>2,302 (-1.5%)</td>
<td>2,110 (-3.9%)</td>
<td>2,022 (-5.0%)</td>
</tr>
<tr>
<td>Throughput</td>
<td>0% HVP</td>
<td>2,854 (na)</td>
<td>2,680 (na)</td>
<td>2,340 (na)</td>
</tr>
<tr>
<td>(Percentage Difference**)</td>
<td>5% HVP</td>
<td>2,822 (-1.1%)</td>
<td>2,604 (-2.8%)</td>
<td>2,204 (-5.8%)</td>
</tr>
<tr>
<td>MPR=80%</td>
<td>10% HVP</td>
<td>2,786 (-2.4%)</td>
<td>2,586 (-3.5%)</td>
<td>2,158 (-7.8%)</td>
</tr>
<tr>
<td>Throughput</td>
<td>0% HVP</td>
<td>2,200 (na)</td>
<td>2,200 (na)</td>
<td>2,200 (na)</td>
</tr>
<tr>
<td>(Percentage Difference**)</td>
<td>5% HVP</td>
<td>2,200 (0.0%)</td>
<td>2,200 (0.0%)</td>
<td>2,000 (-9.1%)</td>
</tr>
<tr>
<td>HCM 2010***</td>
<td>10% HVP</td>
<td>2,200 (0.0%)</td>
<td>2,200 (0.0%)</td>
<td>1,833 (-16.7%)</td>
</tr>
</tbody>
</table>

*Lane number 1 indicates the most inner lane, and lane number 4 indicates the most outer lane; **Throughput percentage difference is respected to 0% HVP; throughput percentage difference 0% HVP is not applicable (na). ***HCM 2010 is under conventional manual driving.

On the other hand, by looking at the multiple MPRs in Figure 7a and 7b, for all the four lanes, the throughput increases as the MPR increases under all the HVPs. Moreover, it is observed from Figure 7 that, a larger MPR experiences with a larger throughput difference between lanes. This is because the maximum and the minimum speed limit both decrease when a passenger car switches from lane 2 to lane 3 and it will offset the benefit brought by a rising CACC car MPR.

Figure 7. Throughput of each lane under different heavy vehicle proportions with 0% CACC HV MPR
By referring to the case when the HVP is 0%, the impact of DPLSL is observed on the traffic flow. It’s interesting to find that the throughputs of the four lanes are not decreasing in the order from lane 1 to lane 4. The possible reason why the throughput of lane 4 is larger than that of lane 3 in some cases is that because of the speed limit differential, the passenger cars on lane 3 is under more “pressure” than those of lane 4 since it is adjacent to a lane with a higher maximum and minimum speed limit. Thus, the drivers of passenger cars are more willing to drive on lane 4. This may also be the reason why the throughput of lane 4 is larger than that of lane 3 under the 5% HVP case. Also, due to the differential speed limit of both maximum and minimum speed limit from lane 2 to lane 3, throughput of lane 3 is less than lane 2 even at high CACC car MPRs and such decreases in throughput from lane 2 and lane 3 were regardless of the HVPs.

Lastly, in the existing traffic with 90% of passenger cars in a 60% CACC car MPR, the authors consider and compare 10% of HV with and without CACC. Results are documented in Table 5 below.

Table 5. Throughput and Percentage Difference in a Composition of a 10% of Heavy Vehicles with and without CACC, and a 90% of Passenger Cars with 60% CACC Car MPR

<table>
<thead>
<tr>
<th>Lane No.*</th>
<th>Lane 1 (Throughput)</th>
<th>Lane 2 (Throughput)</th>
<th>Lane 3 (Throughput)</th>
<th>Lane 4 (Throughput)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10% of HV without CACC</td>
<td>10% of HV with CACC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10% of HV without CACC</td>
<td>2,302 (na)</td>
<td>2,110 (na)</td>
<td>2,022 (na)</td>
<td>1,982 (na)</td>
</tr>
<tr>
<td>10% of HV with CACC</td>
<td>2,316 (+0.6%)</td>
<td>2,142 (+1.5%)</td>
<td>2,133 (+5.5%)</td>
<td>2,130 (+7.5%)</td>
</tr>
</tbody>
</table>

*Lane number 1 indicates the most inner lane, and lane number 4 indicates the most outer lane;

**Throughput percentage difference is respected to 10% HVP without CACC; throughput percentage difference for 10% HVP without CACC is not applicable (na).

Table 5 shows the throughput and percentage difference with 0% and 100% CACC HV MPRs in a 10% HVP and with a 60% CACC car MPR in a 90% Passenger Car Percentage. When the HVs on HV non-restricted lanes (lane 3 and lane 4) are all CACC equipped, the increase of throughput in HV restricted lanes (lane 1 and lane 2) are relatively small. There is a 7.5% increase on the throughput of HV restriced lanes, which means the CACC equipped HVs can improve the traffic operation states. Moreover, after the introduce of CACC equipped HVs, the throughputs of lane 3 and lane 4 are quite close. Same trend is found when the CACC car MPR is 80%. This result encourages future study on the benefits of CACC HVs in multilane highways.

CONCLUSIONS

Although many existing literatures have evaluated the impact of CACC technology on multi-lane highway, there are only few studies that considers the existence of HVs as well as lane management measures which may co-exist with CACC cars frequently for the forthcoming years. DPLSL policy, as a common lane management measure adopted by countris like China and Thailand, is widely discussed recently and may have potential impact on the lane-changing behavior. Thus, the objective of this study is to explore the impact of CACC technology under a
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more realistic and complex environment—multilane highway with HVs and DPLSL policy and
to find out whether the CACC technology can still benefit the traffic system in this case.

This paper is based on a microscopic simulation by CA models. The results showcased
the impact of CACC on a multilane highway with a DPLSL policy. As the same as researchers
observed on multilane highway with uniform speed limit policy (10), the existence of CACC
cars increases the throughput as the CACC car MPR rises. However, such increase is only
sharper when the CACC MPR exceeds 60%. When MPR reaches 100% with a 10% HVP, the
throughput of the lanes can be increased by 78% at most. The existence of HVs will cause a
1.5%~15.7% reduction on the throughput of all the lanes even under high CACC car MPRs
(60% and 80%).

Under the DPLSL policy with differential speed limit of both maximum and minimum
speed limit, drops in throughputs from HV restricted lanes to non-restricted lanes existed even at
high CACC MPRs (60% and 80%). Such decreases in throughput were regardless of the HVPs.
CACC HVs will bring a 7.5%~7.9% increase on the throughput of HV non-restricted lanes, but
no obvious increase on those of HV restricted lanes. When there is no HV on the lane, different
from the theoretical capacity estimated from HCM 2010 which remain the same, reduction is still
observed by CA model.

The contribution of the study is as follows. The impact of CACC technology is evaluated
in a more realistic perspective by considering the existence of HVs and the implementation of
DPLSL policy. The growth pattern of lane throughputs over different CACC car MPRs with the
existence of heavy vehicles and the implementation of DPLSL policy is presented; the combined
effect of an increasing HVPs as well as the DPLSL policy to the traffic network is studied. There
are several limitations of this study. The first is that the studied highway segment is simple. In
the future study, more complex scenario (i.e., waving segment) can be studied and more
comprehensive lane-changing model can be applied. Also, it would be interesting to investigate
the comparison of CACC impact between the uniform speed limit and the differentiated per-lane
speed limit. Moreover, existing studies on CACC equipped HVs are still quite limited. There has
already been a report (13) investigating the potential of HVs on CACC performance and found
that “connectivity at medium to high market penetration rates (> 60%) can improve traffic
throughput compared to the baseline case of 100 percent isolated-manual vehicles”, which is in
line with our study. The literature also talks about truck platooning and its impact relying on
CACC technology. In our future studies, CACC equipped HVs can be considered in a more
detailed way.

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REFERENCES


