

**Using Cooperative Adaptive Cruise Control (CACC) to Form High-  
Performance Vehicle Streams:  
Simulation Results Analysis**

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## INTRODUCTION

This document contains detailed simulation results analysis and discussion for the Federal Highway Administration (FHWA) Exploratory Advanced Research (EAR) project entitled *Using Cooperative Adaptive Cruise Control (CACC) to Form High-Performance Vehicle Streams*. The objective of this study is to obtain authoritative predictions of traffic impacts of ACC and CACC at various market penetrations and define the CACC operation strategies that create the most capacity and throughput improvement in the freeway traffic stream. A microscopic traffic simulation environment has been developed for quantifying the capacity and throughput improvements. The performance of each analysis scenario is quantified via systematic mobility indicators estimated based on the simulation data.

In addition to this report, a comprehensive literature review regarding the existing CACC operation strategies has been given in the interim report entitled *Using Cooperative Adaptive Cruise Control (CACC) to Form High-Performance Vehicle Streams Definitions, Literature Review and Operational Concept Alternatives*. The simulation methodology is reported in *Using Cooperative Adaptive Cruise Control (CACC) to Form High-Performance Vehicle Streams: Microscopic Traffic Modeling*. The calibration and validation of the simulation models is elaborated in a separate report entitled *Using Cooperative Adaptive Cruise Control (CACC) to Form High-Performance Vehicle Streams: Microscopic Traffic Model Calibration and Validation*. A higher-level summarization of the methodology, study results and discussion, and implementation recommendations can be found in the project final report: *Using Cooperative Adaptive Cruise Control (CACC) to Form High-Performance Vehicle Streams: Final Report*.

## CACC OPERATIONAL ALTERNATIVES USED IN THIS STUDY

Although there are many CACC operational alternatives reported in literature, this study narrows the considerations to the alternatives that are likely to be implemented soon, without requiring major upgrade of the existing road infrastructure. Particularly, the CACC operation strategies analyzed in this study are listed as follows:

- Implementation of manually driven vehicles equipped with the Vehicle Awareness Device (VAD). The VAD vehicles have the wireless communication capability. They can broadcast real-time information regarding their operation status and route choice. Although they don't have automated controllers to perform the car-following task, they can serve as the leader of CACC vehicle strings. With this strategy, the probability for CACC vehicles to travel in the CACC mode increases at low CACC market penetration levels. It thus offers incentives for users to equip CACC, even when the CACC market penetration is low.
- Implementation of CACC managed lane (ML). The managed lane strategy has been widely used to serve high occupancy vehicles or drivers willing to pay a toll, with the purpose of improving the overall efficiency of the highway system. The CACC managed lane can adopt a similar operation concept that only allows CACC vehicles and VAD vehicles to enter the managed lane. It physically separates the CACC traffic stream and the regular traffic. As the CACC vehicles concentrate in the managed lane, they will have larger probability to travel in CACC strings. The managed lane also reduces the interactions between the CACC vehicles and manually driven vehicles. The CACC strings are less likely to be interrupted in the managed lane.
- Discouraging discretionary lane changes for CACC string leaders and followers (DLC restriction). This strategy can be achieved by using an on-board device that offers real-time lane change guidance for drivers. When a driver is in a CACC string, we expect that her or his lane change behaviors will be different from what the driver would normally do. Although there is no empirical data quantifying the behavior change, we can perform the what-if analysis to determine the outcomes if we offer the lane change guidance or restrictions to the CACC drivers. With this strategy, the drivers are encouraged to stay in the CACC string whenever possible. In this case, the disturbances caused by the CACC drivers' lane change maneuvers can be reduced. The CACC string will therefore have a higher probability of operating in a steady state.
- Making drivers stay in the CACC mode when they cannot find a gap in the target lane. This strategy applies to CACC drivers when they try to make a lane change, but the current gap in the target lane is not acceptable. In this case, the driver will continue driving in the CACC mode, instead of turning off the CACC and manually accelerating or decelerating for gap searching. This strategy can reduce the probability that the CACC strings are broken down due to drivers' mode switching.
- Offering early lane change advisory messages for drivers that want to exit the freeway. This strategy is expected to help improve the traffic flow for the freeway diverging areas under high CACC market penetration. As the traffic volume

increases with the CACC market penetration, the traffic flow density will become high, which makes it difficult to make lane changes toward the off-ramp. When the driver is close to the exit but still cannot merge into the off-ramp, she or he might take aggressive lane changes to force into the target lane, potentially causing significant disturbances to the traffic flow. If the early lane change advisory message is provided, the driver can start making lane changes at a longer distance upstream from the exit. In this case, she or he will have larger chance to find an acceptable gap such that the driver does not have to force into the target lane. Reducing the aggressive lane change behaviors can stabilize the traffic flow, and subsequently lower the probability of breaking the operation of CACC vehicle strings.



# IMPACT OF CACC OPERATION ON SIMPLE NETWORK

## DESCRIPTION OF THE STUDY NETWORK

The simple network analyzed in this study is illustrated in Figure 1. The network is a four-lane freeway with an on-ramp and an off-ramp. The freeway mainline is about 7 kilometers long. The source links in the network are highlighted by the red boxes. The simulated vehicles are released into the network through the source links. There is a ‘warm-up’ mainline segment which is 2 kilometers long downstream from the mainline source link. Vehicles will use this segment to reach a stable car-following state after entering the network. This segment also allows CACC vehicles to form stable CACC vehicle strings. Because the traffic stream in this upstream segment has a flow status transition that does not happen in real-world traffic, the data from that segment is eliminated from our analysis.

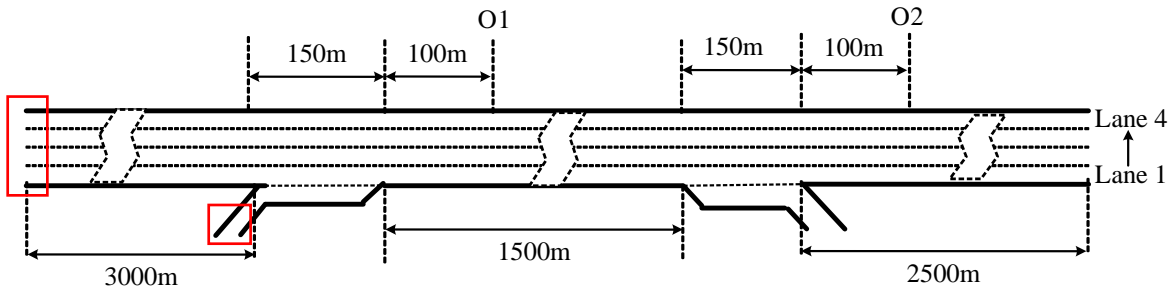


Figure 1. Sketch plot of simple network.

## ANALYSIS SCENARIOS AND PERFORMANCE MEASURES

Our analysis started with the identification of the pipeline capacity of the simple network. Results of the analysis can reveal the impact of the CACC string operation on the basic freeway segment. To this end, we specified zero on-ramp and off-ramp traffic flows and then measured the traffic flow of the four-lane freeway network under various CACC market penetrations. The pipeline capacity was defined as the maximum 15-minute moving average flow rate observed in the middle of the network, according to the Highway Capacity Manual (HCM, 2010). The experiments began with simulating a constant and relatively low traffic volume for one hour. If the freeway remained free-flowing, then subsequent simulations were conducted with slightly higher volume input (e.g., plus 1000 veh/hr), until the highest observed 15-minute moving average flow no longer increased as the input became larger. The capacity was finally determined based on five replications with different random seeds. These procedures were simulated for 0%, 20%, 40%, 60%, 80%, and 100% market penetration of CACC equipped vehicles.

The next study concerned the performance of the freeway merge bottleneck under various CACC market penetrations. The on-ramp merging area depicted in Figure 1 was used for the study. In the analysis, we fixed the freeway mainline traffic input at the pipeline capacity measured under the different CACC market penetration cases in the previous study. The on-ramp traffic volume increased from 300 veh/hr to 1500 veh/hr, in 300 veh/hr increments. In each simulation run, the mainline traffic was first released for 20 minutes. Afterwards, the on-ramp traffic was loaded together with the mainline traffic for 40 minutes. In the last 10 minutes of the simulation, both upstream mainline and on-ramp traffic volume were set to zero. The vehicles remaining in the network could leave the simulated freeway in that period. The freeway throughput was observed at the location O1 as shown in Figure 1. In the analysis, we only used the traffic data collected in the last 30 minutes of the 40-minute period when the on-ramp traffic was loaded. The first 10-minute data were eliminated because the traffic flow may experience fluctuations and/or breakdown as the on-ramp traffic first enters the freeway mainline. Such a flow fluctuation can lead to an unstable queue discharging flow. The 15-minute moving average flow rate was computed based on the 30-minute data. The maximum 15-minute flow rate was considered as the throughput of the merging area.

The last study with the simple network was performed at the off-ramp diverging area depicted in Figure 1. The study revealed the percentage of the mainline traffic that could exit the freeway without causing traffic breakdown. In the analysis, we made the mainline traffic input equal to the pipeline capacity under various CACC market penetrations. The off-ramp traffic was initially set as 5% of the mainline flow. Additional simulation runs were performed for the off-ramp traffic percentages of 10%, 15%, 20% and 25% as well. The traffic flow was measured at the location O2 as shown in Figure 1. The simulation time was 1 hour and the data for the last 40 minutes were used to compute the 15-minute moving average flow rate. The highest 15-minute moving average flow rate was considered as the throughput of the diverging bottleneck.

The impact of the CACC operation strategies on the capacity and throughput improvement was also analyzed for the pipeline, on-ramp bottleneck, and off-ramp bottleneck cases. The above analysis processes were performed with and without the operation strategies. The ML strategy was tested for the 40%, 60%, and 80% CACC market penetration cases. In the 20% penetration case, the CACC vehicles in the fleet were not enough to fully occupy a lane. The VAD strategy was tested for cases with 20%, 40%, 60% and 80% CACC market penetration. The DLC restriction strategy was analyzed in all CACC cases. The lane change advisory strategy was applied in the off-ramp analysis only.

## **DETERMINATION OF MAXIMUM CACC STRING LENGTH AND INTER-STRING TIME GAP**

We have identified the maximum CACC vehicle string length and the inter-string time gap to be implemented in the CACC string operation. These parameters are particularly important for achieving good traffic mobility performance at on-ramp and off-ramp areas where the merging or exiting vehicles make frequent mandatory lane changes. With

suitable levels for the two parameters, we can achieve both significant improvement of the freeway capacity and throughput, and stable traffic flow where the merging and exiting vehicles can easily find acceptable gaps in the target lane to merge into, without causing severe disturbances.

The analysis was performed in the simple network under 100% CACC market penetration. The on-ramp and off-ramp traffic volumes were fixed at 500 veh/hr. The tested levels of the maximum string length were 5, 10, 15, 20, and 25; and the inter-string time gaps were 1.0, 1.5, 2.0 and 2.5 seconds. The experiments began with simulating a constant and relatively low mainline traffic volume for one hour. If the freeway remained free-flowing, then subsequent simulations were conducted with slightly higher volume input (e.g., plus 1000 veh/hr), until the highest observed 15-minute moving average flow no longer increased as the input became larger. Then we measured the maximum 15-minute throughput at both the on-ramp and off-ramp area (locationsb O1 and O2 in Figure 1) as the performance metrics.

The freeway throughput at the on-ramp and off-ramp location is listed in Tables 1 and 2. When the inter-string gap is 1.0 second, the freeway throughput increases with the maximum string length when the maximum length is 15 or less. When the maximum length becomes longer, it becomes more difficult for the merging and diverging vehicles to find acceptable gaps in the target lane. In this case, those vehicles have to make aggressive lane changes, thus creating traffic disturbances that lead to traffic breakdown. Under this traffic condition, the throughput declines with increasing string length. When the inter-string gap is 1.5 seconds or larger, the throughput reduces linearly with the inter-string time gap at both the on-ramp and off-ramp site. On the other hand, the throughput increases with the string length, although the increase becomes smaller after the string length is larger than 15. The throughput increase does not have a linear pattern with the string length because longer strings can negatively impact the traffic operation at the on-ramp and off-ramp sections. Such a negative impact offsets the throughput increase that otherwise could have been achieved with longer strings.

**Table 1. Freeway throughput (veh/hr/ln) at the on-ramp area under various maximum CACC string length and inter-string time gap levels.**

| <i>Max string length</i> | <i>Inter-string time gap (s)</i> |            |            |            |
|--------------------------|----------------------------------|------------|------------|------------|
|                          | <b>1.0</b>                       | <b>1.5</b> | <b>2.0</b> | <b>2.5</b> |
| <b>5</b>                 | 3105                             | 2809       | 2425       | 2157       |
| <b>10</b>                | 3371                             | 3084       | 2793       | 2534       |
| <b>15</b>                | 3465                             | 3235       | 3010       | 2762       |
| <b>20</b>                | 3201                             | 3312       | 3135       | 2936       |
| <b>25</b>                | 2824                             | 3364       | 3226       | 3045       |

**Table 2. Freeway throughput (veh/hr/ln) at the off-ramp area under various maximum CACC string length and inter-string time gap levels.**

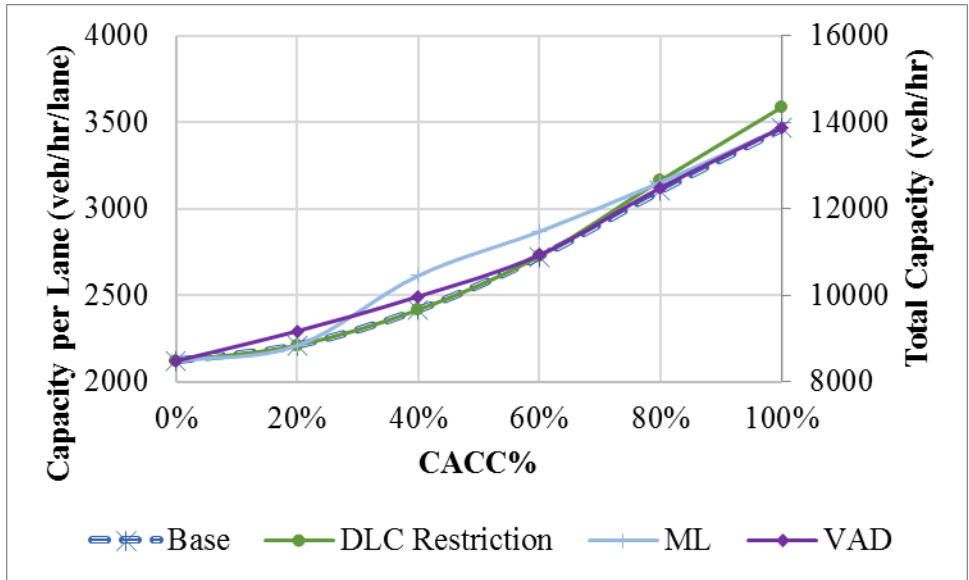
| <i>Max string length</i> | <i>Inter-string time gap (s)</i> |            |            |            |
|--------------------------|----------------------------------|------------|------------|------------|
|                          | <b>1.0</b>                       | <b>1.5</b> | <b>2.0</b> | <b>2.5</b> |
| <i>5</i>                 | 3115                             | 2822       | 2422       | 2157       |
| <i>10</i>                | 3335                             | 3078       | 2797       | 2536       |
| <i>15</i>                | 3474                             | 3265       | 3016       | 2770       |
| <i>20</i>                | 3139                             | 3317       | 3149       | 2934       |
| <i>25</i>                | 2808                             | 3367       | 3234       | 3046       |

Based on the above analyses, we recommend that the maximum string length should be in the range between 10 and 15; and the inter-string gap should be between 1.0 and 1.5 seconds. With those parameter levels, the traffic stream at the freeway on/off-ramp bottlenecks can reach a high-level throughput, while stable string operations can also be maintained. In the following capacity and throughput analyses, we have used the maximum string length of 10 and the inter-string time gap of 1.5 seconds. We adopted the conservative end of the recommended range because our analysis scenarios might have on-ramp and off-ramp traffic inputs larger than 500 veh/hr. Using those parameter levels can lower the probability of traffic breakdown for those challenging analysis cases.

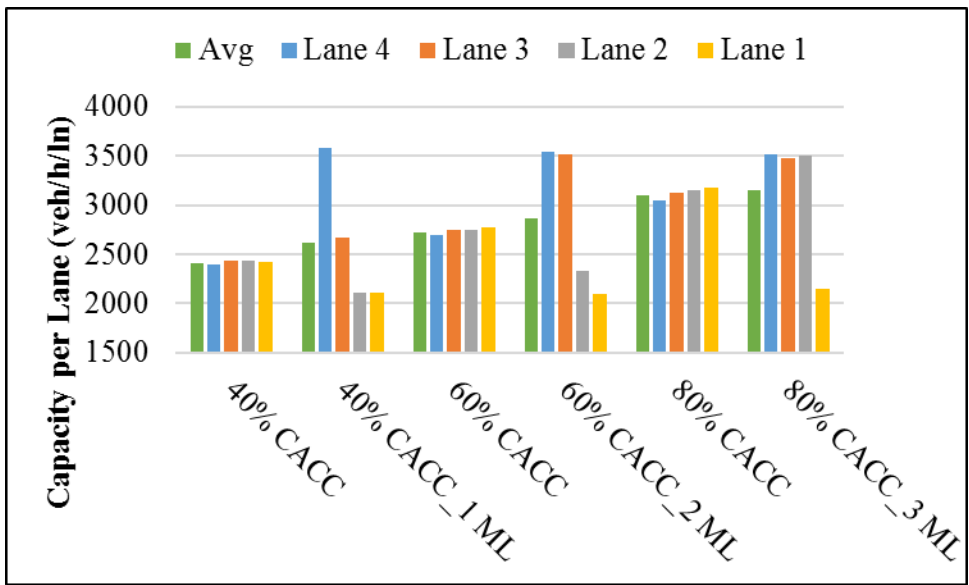
## **PIPELINE CAPACITY OF MULTI-LANE FREEWAY**

Figure 2 shows the freeway mainline capacity as a function of the CACC market penetration, under various CACC operation strategies. The curve of the base case shows the results when no strategy was implemented. The ML strategy was applied only at 40%, 60% and 80% CACC market penetrations. At 40% penetration, the leftmost lane of the freeway was operated as the managed lane; whereas at 60% penetration the two leftmost lanes and at 80% penetration the three leftmost lanes. The VAD was evaluated between 20% and 80% CACC market penetrations. It was assumed that all manually driven vehicles were equipped with the VAD. The DLC restriction strategy was implemented for all CACC market penetrations.

The curve of the base case has a quadratic trend, which indicates that the capacity increases more rapidly once the market penetration of CACC equipped vehicles becomes larger. At 100% market penetration, the freeway capacity is roughly 63% higher than at 0% market penetration. The results also indicate that the ML strategy can bring about more capacity improvement at 40% and 60% penetrations than at 80% penetration. For the VAD strategy, the most significant benefit is observed at lower penetration cases (e.g., 20% and 40%); whereas the DLC restriction strategy works better at high penetration cases (e.g., 80% and 100%).



**Figure 2. Freeway pipeline capacity at different CACC market penetrations.**



**Figure 3. Pipeline capacity of individual lanes with and without managed lanes (lane 4—leftmost lane, lane 1—rightmost lane).**

The ML strategy has two major effects on the traffic flow. It increases the number of CACC vehicle strings in the managed lane and thereby increases the capacity of that lane. On the other hand, the strategy reduces the CACC penetration in the general-purpose lanes and thus makes their capacity lower. Figure 3 quantifies the two effects by indicating the capacity of individual lanes. In the figure, lane 4 represents the leftmost lane and lane 1 is the rightmost lane. At 40% and 60% CACC market penetrations, the capacity increase of the managed lanes is substantially larger than the capacity decrease of the general-purpose lanes, leading to an overall improvement of the freeway capacity. At 80% penetration,

however, the capacity of each lane is already at a high level without the ML strategy. After the managed lane is implemented, the capacity reduction of the general-purpose lane is so great that it offsets the capacity increase of all three managed lanes. Figure 3 also indicates that the ML strategy significantly changes the distribution of traffic load across the four freeway lanes—there is more traffic in the managed lane and less traffic in the general-purpose lane. As the traffic flow in the rightmost lane (lane 1) becomes smaller, there should be more gaps in the traffic stream. In this case, the rightmost lane might serve more on-ramp traffic. The freeway performance with on-ramp traffic inputs is discussed in the next subsection.

Because the VAD strategy makes it possible for every CACC vehicle to find a CACC vehicle string leader (any manually driven vehicle), it increases the probability that a CACC vehicle operates in a CACC string. Without the VAD strategy, the probability that a CACC vehicle is in a CACC string can be estimated by equation 1; and the probability that a vehicle is in a CACC string is estimated by equation 2:

$$\begin{aligned}
 P(\text{a CACC vehicle in string}) & \\
 &= 1 - P(\text{preceding vehicle is not a CACC vehicle}) \quad (1) \\
 &\quad \cdot P(\text{following vehicle is not a CACC vehicle})
 \end{aligned}$$

$$\begin{aligned}
 P(\text{a vehicle in string}) & \\
 &= P(\text{in string}|\text{CACC}) \cdot P(\text{CACC}) \quad (2) \\
 &\quad + P(\text{in string}|\text{manual vehicle}) \cdot P(\text{manual vehicle})
 \end{aligned}$$

$$\begin{aligned}
 P(\text{in string}|\text{manual vehicle}) & \\
 = \begin{cases} 0 & \text{without VAD} \\ P(\text{following vehicle is a CACC vehicle}) = P(\text{CACC}) & \text{with VAD} \end{cases} \quad (3)
 \end{aligned}$$

where

$P(\text{in string}|\text{manual vehicle})$ : the conditional probability that a manually driven vehicle operates in the CACC vehicle string.

$P(\text{in string}|\text{CACC})$ : the conditional probability that a CACC vehicle operates in the CACC vehicle string, which can be computed by equation 1.

To compare with and without VAD case, Table 1 lists the probability for a CACC vehicle to operate in a CACC vehicle string under various CACC market penetrations; and Table 2 lists the probability that any vehicle operates in a CACC string. Table 1 represents the likelihood that a CACC vehicle actually uses the CACC in the traffic stream; whereas Table 2 indicates the probability that any vehicle in the traffic stream is involved in a CACC vehicle string operation. Both tables suggest that the VAD strategy brings about substantial increases in CACC string operations at low and medium CACC market penetrations. When the CACC market penetration grows to 80%, the benefit of the strategy is only marginal. The theoretical probability analysis explains the observation that the VAD

strategy only creates capacity increases at medium and low CACC market penetration cases.

**Table 3. Probability that a CACC vehicle operates in a CACC string.**

|                    | CACC Market Penetration |      |      |      |
|--------------------|-------------------------|------|------|------|
|                    | 20%                     | 40%  | 60%  | 80%  |
| <b>Without VAD</b> | 36%                     | 64%  | 84%  | 96%  |
| <b>With VAD</b>    | 100%                    | 100% | 100% | 100% |
| <b>Difference</b>  | 64%                     | 36%  | 16%  | 4%   |

**Table 4. Probability that any vehicle is involved in a CACC string operation.**

|                    | CACC Market Penetration |       |       |       |
|--------------------|-------------------------|-------|-------|-------|
|                    | 20%                     | 40%   | 60%   | 80%   |
| <b>Without VAD</b> | 7.2%                    | 25.6% | 50.4% | 76.8% |
| <b>With VAD</b>    | 36%                     | 64%   | 84%   | 96%   |
| <b>Difference</b>  | 28.8%                   | 38.4% | 33.6% | 19.2% |

The DLC restriction strategy has little impact when the CACC market penetration is 60% or lower. In these cases, the manually driven vehicles will make discretionary lane changes regardless of whether the strategy is implemented. As the manually driven vehicles make discretionary lane changes, they create disturbances to the traffic stream, and this eventually affects the CACC string operation. At high CACC market penetrations, most drivers are affected by the strategy. In this case, it can significantly reduce the number of discretionary lane changes. In addition, the traffic density is much higher in the high CACC market penetration cases. Reducing the lane change disturbances can bring about greater improvement in the heavy traffic flow than in the light traffic flow.

We can also compare the simulation results with the theoretical capacity. When the CACC market penetration is 100%, the theoretical capacity can be reached in ideal car-following conditions—without disturbances caused by the lane change maneuvers, no heterogeneous behaviors among drivers, and perfect CACC vehicle string operations. The theoretical capacity is defined as the following (Varaiya, 1993):

$$C = \bar{v} \frac{n}{n \cdot \bar{l} + (n - 1) \cdot \bar{v} \cdot T_1 + \bar{v} \cdot T_2} \cdot 3600 \quad (4)$$

where

$\bar{v}$ : average desired speed (m/s),  $\bar{v} = 30$  m/s in this study.

$n$ : maximum string length in number of vehicles,  $n = 10$  in this study.

$\bar{l}$ : average vehicle length (m),  $\bar{l} = 5$  m in this study.

$T_1$ : intra-string constant time gap (s), based on the time gap distribution, the expected value is  $T_1 = 0.6s \cdot 57\% + 0.7s \cdot 24\% + 0.9s \cdot 9\% + 1.1s \cdot 12\% = 0.72 s$ .

$T_2$ : inter-string time gap (s),  $T_2 = 1.5 s$  in this study.

Based on the parameters above, the theoretical capacity at 100% market penetration is 3721 veh/hr/lane. As Figure 2 shows, the simulated capacity is about 93% of the theoretical capacity for the base case, 96% for the DLC restriction case. The simulated capacity is lower than the theoretical capacity because of the following reasons:

- Discretionary lane changes cause lateral interactions and additional decelerations, thereby reducing the capacity.
- String leaders may have a lower than average desired speed because the desired speed of the driver population follows a distribution rather than a single deterministic value. This can impede the flow of subsequent vehicles in the CACC string.
- The CACC string may not always operate at its maximum length. When the length is shorter than the maximum, the capacity improvement becomes less.

## **FREEWAY CAPACITY AT MERGING BOTTLENECKS**

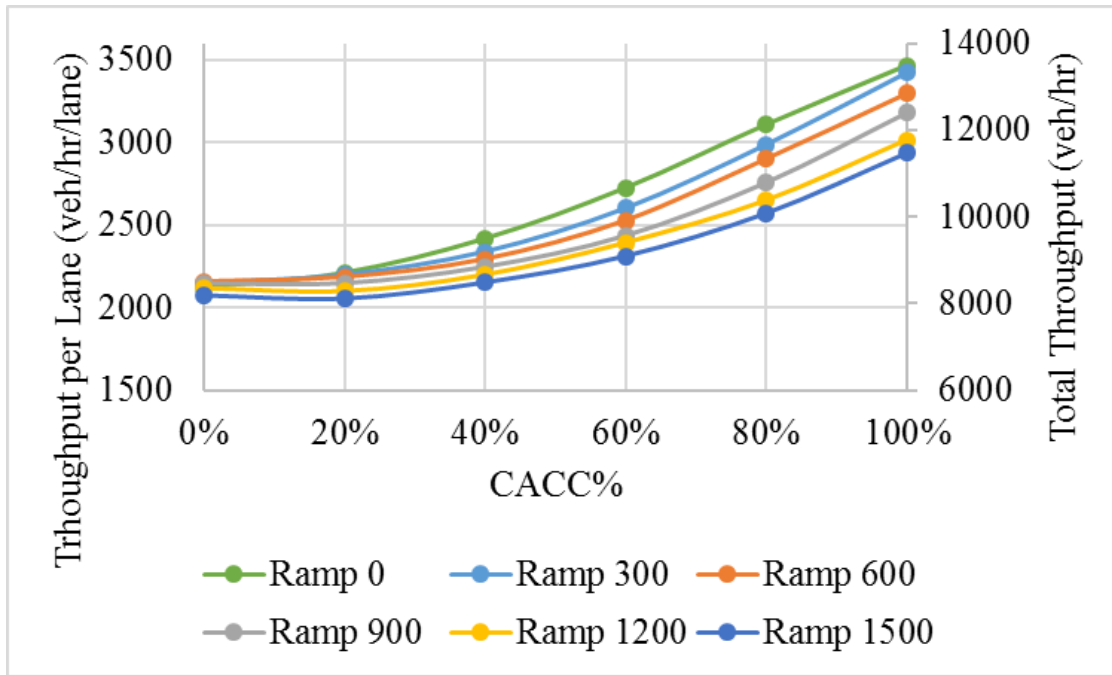
The previous pipeline capacity analysis suggests that the capacity improvement has a quadratic trend with the CACC market penetration. In the following analysis, we will check if such a trend still exists when there is merging traffic from the on-ramp. The on-ramp merging traffic often triggers congestion of the freeway mainline traffic. If the CACC string operation can improve the traffic flow of the merging area, it enhances the overall performance of the freeway network.

Results presented in the previous section also indicate that the ML and VAD strategy may relieve the congestion of a freeway merge bottleneck. The ML can help create extra gaps in the freeway mainline so that the on-ramp traffic can merge into the mainstream more easily. The VAD strategy allows the on-ramp CACC vehicles to join a CACC string leader immediately after they enter the freeway mainline. It thus increases the queue discharging flow rate. The DLC strategy is expected to have little impact on the traffic operation in the merging area because it only affects the discretionary lane change maneuvers, while the merging vehicles must make mandatory lane changes to enter the freeway. For the above reasons, we emphasize the impact analysis of the ML and VAD strategies in this section.

We first examined the freeway throughput when there was no broader CACC operation strategy (see Figure 4). The figure shows that the throughput reduces as the on-ramp traffic increases. But the throughput still has the quadratic trend as the CACC market penetration grows. This finding confirms our expectation that the CACC string operation can improve the performance of the on-ramp merging area. The figure also suggests that the freeway throughput becomes substantially smaller than the freeway capacity when the on-ramp

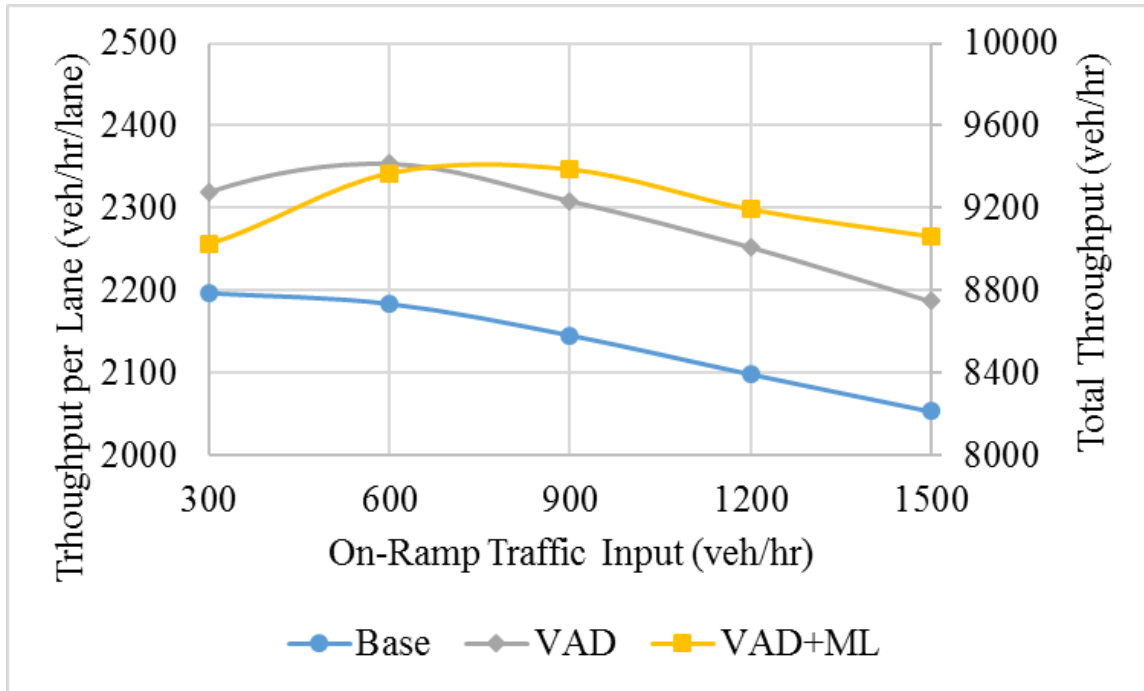


traffic volume grows. In the following analysis, we will show that the freeway throughput can be further improved by implementing CACC operation strategies, even when the on-ramp traffic is at a high level.

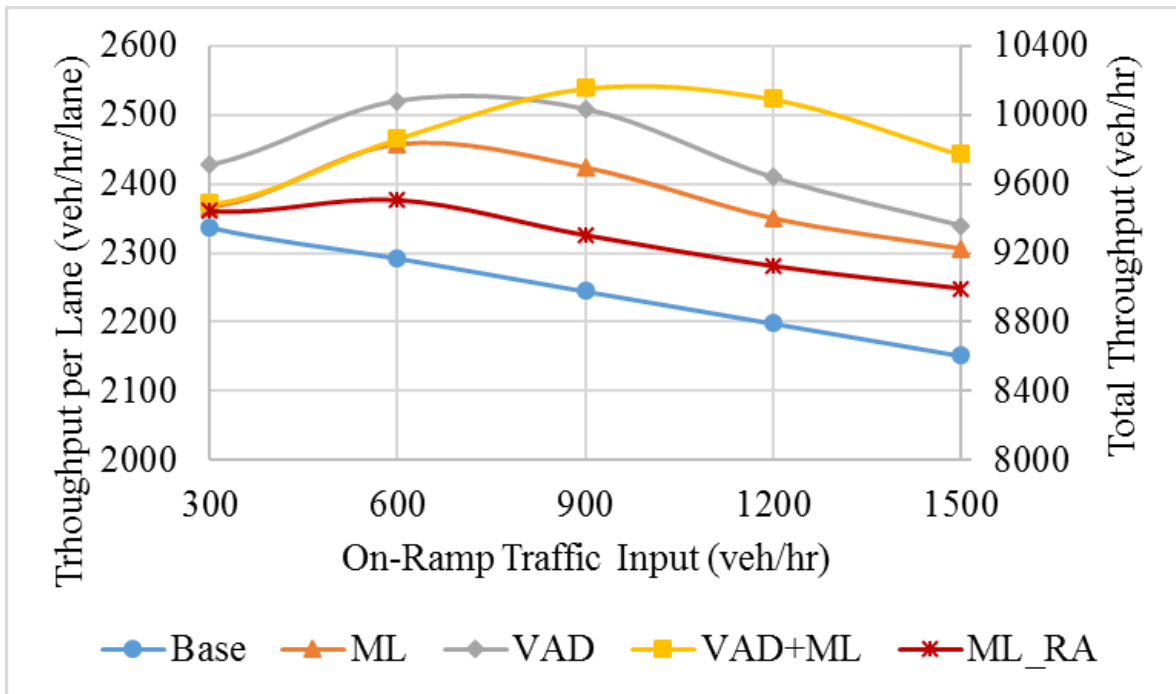


**Figure 4. Throughput of the freeway merge bottleneck.**

After the ML and VAD strategies were implemented, the pattern of the traffic flow became different (see Figures 5 to 8). The freeway throughput first increases as the on-ramp traffic volume grows from 300 veh/hr to 600 veh/hr because the freeway mainline can serve more on-ramp traffic without traffic breakdown. When the on-ramp traffic is 900 veh/hr or more, the merging area becomes congested and the throughput starts decreasing. Nonetheless, the throughput with ML or VAD is still higher than the base case, indicating that those strategies can help improve the traffic flow dynamics even after the traffic becomes congested. Figures 5 to 8 also suggest that the VAD strategy can bring about greater improvement in the throughput than the ML strategy. With the VAD strategy, the CACC vehicles from the on-ramp can easily join a string leader and then exit the merging area in a CACC string. In this case, the queue discharging flow becomes more efficient. With the ML strategy, there are more gaps in the rightmost lane, which allows the on-ramp traffic to merge more easily. But the vehicles remaining in the rightmost lane are mostly manually driven vehicles. In this case, the probability for the on-ramp CACC vehicles to form CACC strings in the merging area is smaller than in the base case. Consequently, the throughput of the rightmost lane becomes smaller under the ML strategy. Such a reduction of the throughput in the rightmost lane offsets the throughput improvement due to the enhanced CACC string operation in the managed lane.



**Figure 5. Throughput of the freeway merging bottleneck under various management strategies and 20% CACC market penetration.**



**Figure 6. Throughput of the freeway merging bottleneck under various management strategies and 40% CACC market penetration.**

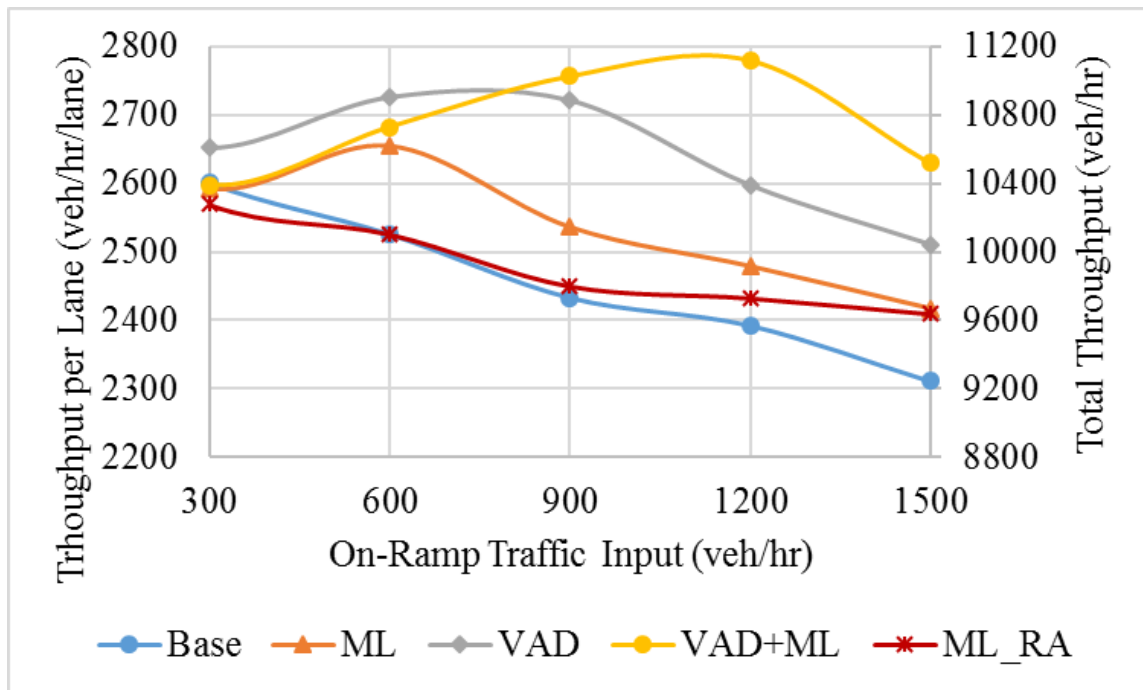


Figure 7. Throughput of the freeway merging bottleneck under various management strategies and 60% CACC market penetration.

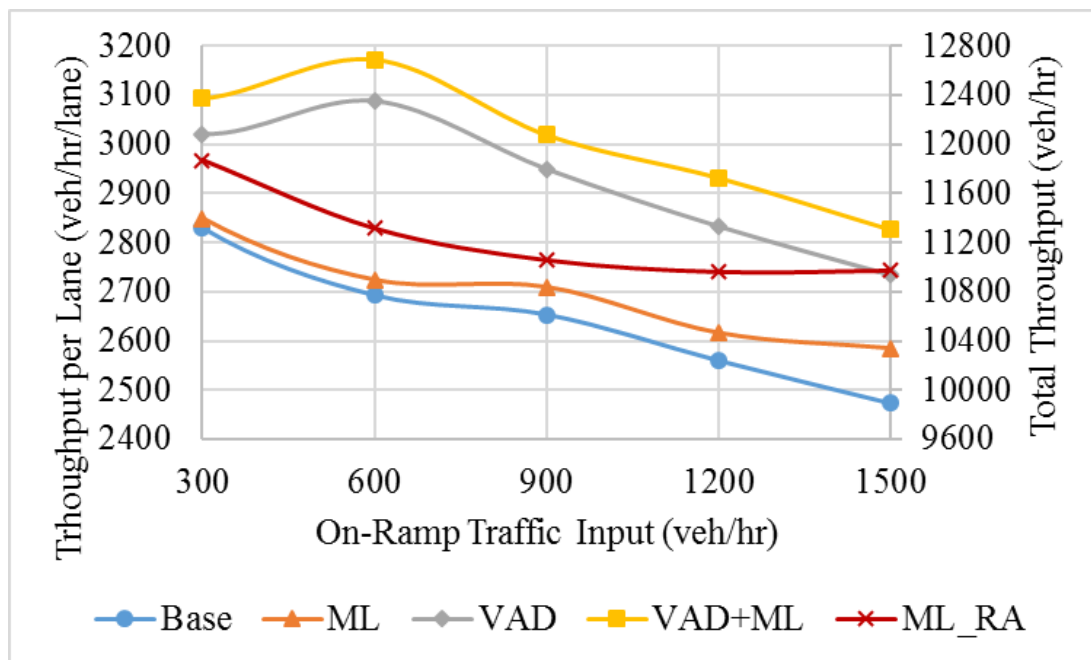


Figure 8. Throughput of the freeway merging bottleneck under various management strategies and 40% CACC market penetration.

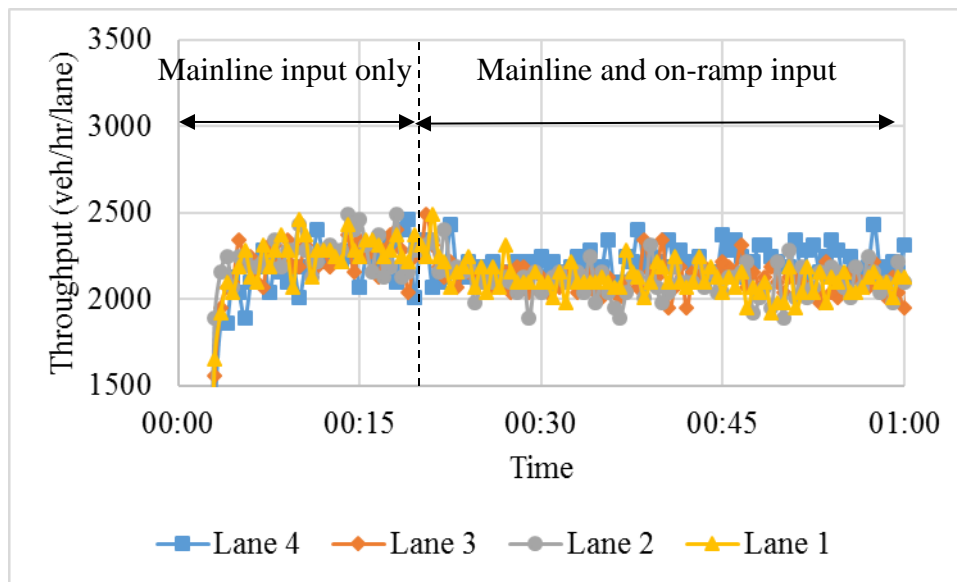
In the previous analysis, we assumed continuous access for the managed lane. The ML strategy can also be applied with restricted access (RA) such that the CACC vehicles may enter and exit the managed lane only at designated ingress and egresses. To test the traffic flow performance under the restricted access operation, we have added a managed lane entry segment in the simulation network. Based on FHWA's guidance (Neudorff et al., 2003), the entry segment is 600 meters downstream from the end of the on-ramp acceleration lane and the length of the entry is 400 meters.

When the restricted access was implemented (ML\_RA curves in Figure 5 through 8), CACC vehicles could not make lane changes from the general-purpose lane to the managed lane upstream from the merging area. In this case, they were unable to create gaps for the on-ramp merging vehicles. When they arrived at the entry point downstream from the merging area, the traffic flow was already in free flow. There was no longer any incentive for them to make lane changes towards the managed lane. Therefore, the managed lane was underused.

As Figure 6 and 7 show, the ML with restricted access performs worse than the ML strategy alone in the 40% and 60% CACC market penetration cases. In the 80% CACC case, the ML with restricted access performs slightly better than the ML alone because when the restricted access is implemented, it prevents vehicles in the rightmost lane from entering the three managed lanes. In this case, the three managed lanes can operate without influence from the on-ramp traffic, and thus suffer smaller capacity reduction. In the meantime, it results in heavy congestion in the rightmost lane and on-ramp. This congestion might lead to queue spillback from the on-ramp to the adjacent arterials. In addition, in the real world, the drivers in the rightmost freeway lane are likely to be tempted to violate the access restriction and merge into the managed lane before reaching the entry segment as they observe much faster traffic in the managed lanes. For the above reasons, the ML strategy with restricted access is not feasible to implement under 40% to 80% CACC market penetration cases.

Since both the ML and VAD strategy can improve the throughput, the performance of the merging area might be further increased if the two strategies are applied at the same time. The results for the combined strategy case are also shown in Figures 5 to 8. Interestingly, the combined strategy only brings about significant benefit when the on-ramp traffic input is 900 veh/hr or higher at 20% to 60% CACC market penetration cases. Under lower on-ramp inputs, the effect of the combined strategy is almost identical to that of the ML strategy alone. It suggests that the VAD strategy does not create extra improvement at low on-ramp input conditions once the ML strategy is activated. When the ML is implemented, the CACC vehicles are concentrated in the managed lane and most vehicles in the general-purpose lanes are manually driven vehicles. In this case, the VAD strategy won't make much difference because there are not many CACC vehicles left in the general-purpose lanes. When the on-ramp traffic volume is small, only a few CACC vehicles will enter the freeway. These CACC vehicles are not enough to greatly change the fraction of CACC vehicles in the fleet. As the on-ramp traffic input reaches a higher level (e.g., more than 900 veh/hr), the merging CACC vehicles start to significantly shift the fleet composition. The effect of the VAD strategy then becomes more prominent.

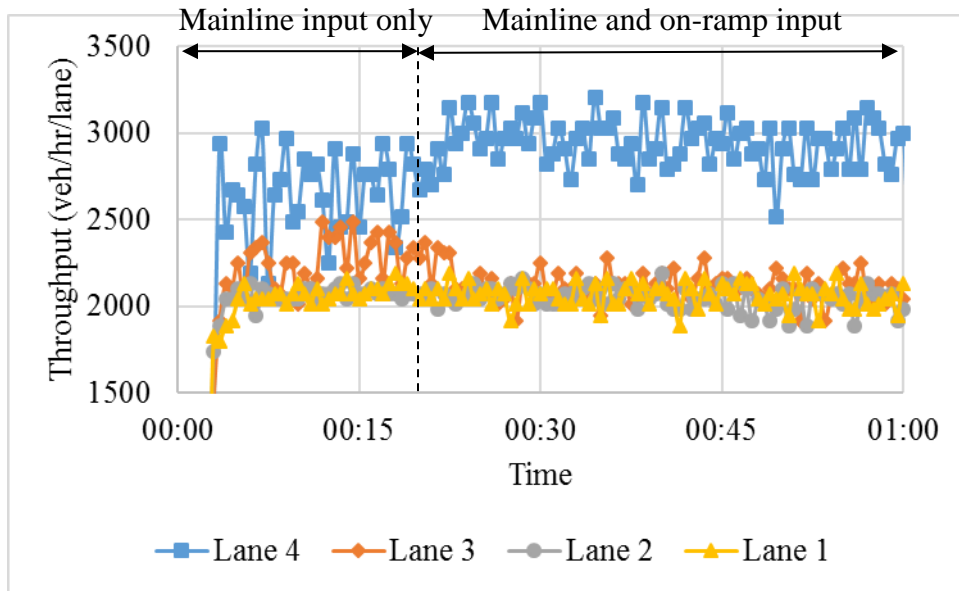
The impact of the ML strategy, VAD strategy, and the combined strategy can also be depicted by the throughput time series plots (see Figures 9 to 12). Under the ML strategy, as heavy on-ramp flow entered the freeway, the general-purpose lanes became congested. In this case, the CACC vehicles used to travel in the general-purpose lanes (especially in lane 3 as shown in Figure 10) were attracted to the managed lane, leading to a significant increase of the throughput of the managed lane and minor throughput decrease for the general-purpose lanes. Comparing Figure 9 and Figure 10, we can find that the general-purpose lanes of the ML case perform similarly to the lanes in the base case. Since the throughput of the managed lane was improved with the ML strategy, the overall throughput of the bottleneck was better in the ML case than in the base case. As Figure 9 and Figure 11 suggest, the VAD strategy leads to throughput improvement because it facilitates a higher queue discharging flow by allowing the on-ramp CACC vehicles to operate in the CACC mode as soon as they merge into the freeway mainline. With this strategy, the throughput of all lanes is higher than in the base case.



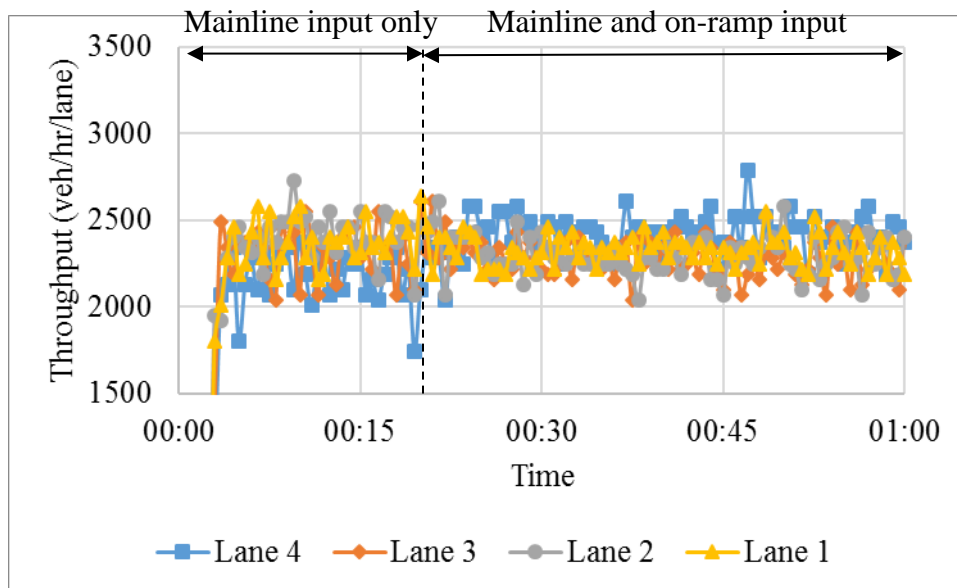
**Figure 9. Freeway throughput time series of the base case (40% CACC, 9600 veh/hr mainline input, 1500 veh/hr on-ramp input).**

When the two strategies are combined, we observe a high throughput for both lane 4 and lane 3. The throughput increase for lane 4 can be attributed to the ML strategy; and the throughput increase for lane 3 is brought about by the VAD strategy. The remaining two general-purpose lanes (lane 1 and lane 2) perform similarly with or without the combined strategy. If we examine the results from the three cases (see Figures 9 to 11), the ML strategy only increases the throughput of the leftmost lane; and the VAD strategy improves the performance of all lanes, but to a moderate degree. With the combined strategy, there is

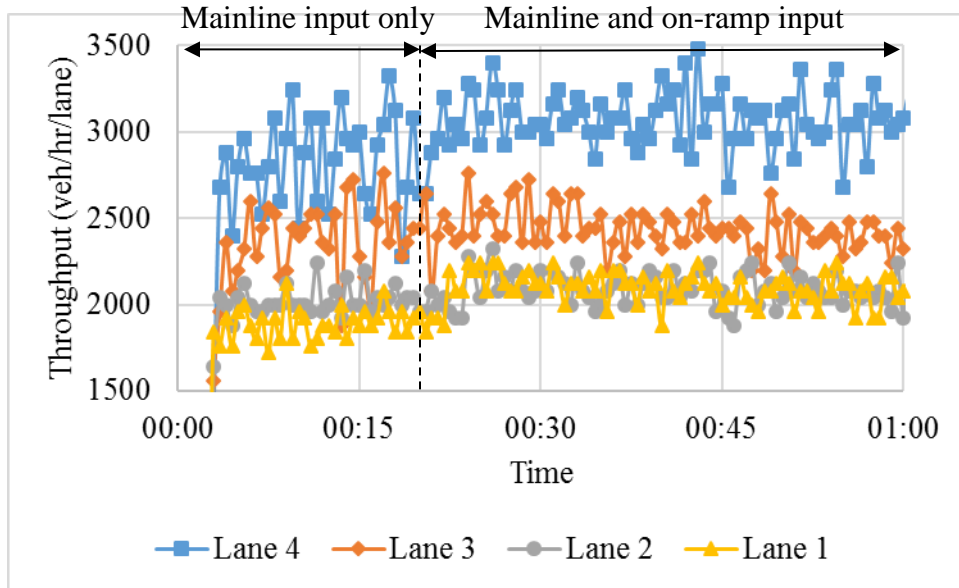
a significant throughput improvement for the left two lanes (i.e., lane 3 and lane 4). Therefore, the combined strategy can outperform the ML strategy and VAD strategy.



**Figure 10. Freeway throughput time series of the ML case (40% CACC, 9600 veh/hr mainline input, 1500 veh/hr on-ramp input).**



**Figure 11. Freeway throughput time series of the VAD case (40% CACC, 9600 veh/hr mainline input, 1500 veh/hr on-ramp input).**

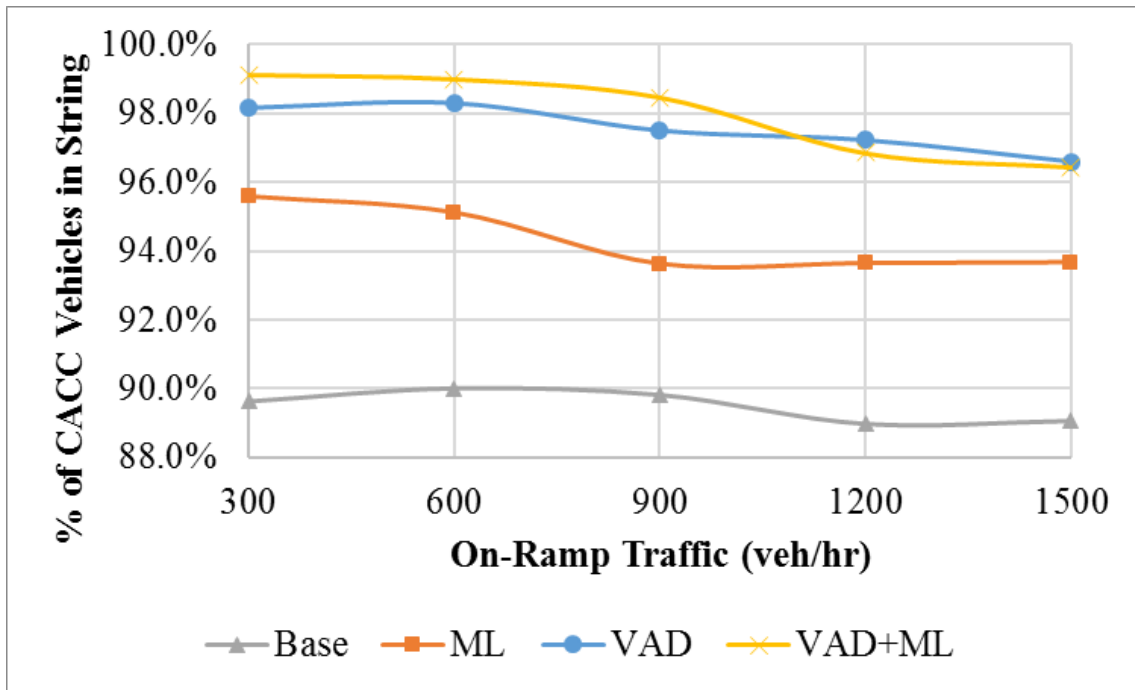


**Figure 12. Freeway throughput time series of the VAD and ML combined case (40% CACC, 9600 veh/hr mainline input, 1500 veh/hr on-ramp input).**

The impact of the traffic management strategies can also be reflected by statistics related to CACC vehicle strings. Here we adopt three statistics: the mean string length (in number of vehicles), the percentage of CACC vehicles operating in CACC strings, and the probability of mode switch from the CACC mode to the manual mode. With the traffic management strategy, we expect to have more CACC vehicles in strings and the strings with longer length. In addition, we want to reduce the probability of the mode switch—it is preferable to make CACC vehicles operate in the CACC mode most of the time. To obtain these statistics, we examine individual CACC vehicles every 2 seconds in a simulation run. At each sampling interval, the driving mode, mode switch status, and string location ID of all CACC vehicles in the study freeway segment are recorded. When the simulation run is completed, the collected data points are used to compute the average string length, the percentage of CACC vehicles in strings, and the probability of the mode switch.

Figures 13 to 16 display the three statistics when the CACC market penetration is 60% with the mainline traffic input of 10,800 vehicles per hour. The conditions for other CACC market penetration cases are similar to the presented plots. As the VAD is implemented in either VAD only case or the VAD and ML combined case, the probability of a CACC vehicle being in a CACC string increases significantly. With the VAD, almost all CACC vehicles can operate in the CACC string because they can always find a string leader, either a VAD vehicle or another CACC vehicle. This finding is consistent with the theoretical analysis listed in Table 1. The ML strategy can also increase the probability because CACC

vehicles can easily join CACC strings in the managed lane. On the other hand, the VAD strategy slightly reduces the mean string length as it increases the number of 2-vehicle strings consisting of a VAD leader and a CACC follower. The ML strategy can significantly increase the mean string length. In the managed lane, the CACC market penetration is 100%, making it easy to form strings with the maximum length. The combined strategy results in a slightly increased mean string length, for it creates both long strings in the managed lane and short strings in the general-purpose lanes. Figure 15 shows the distribution of the string length under different traffic management strategies. We can easily observe the bimodal distribution when the ML strategy is implemented and the large fraction of 2-vehicle strings when the VAD strategy is used. Figure 16 shows that the probability of mode switch is small in all cases. It indicates that the string operation is stable over the study network. The mode switch is observed to occur most often at the merging area where the on-ramp traffic causes disturbances to the mainline traffic. We also find a jump of mode switch probability when the ML strategy is implemented in both the ML only case and the combined case. It indicates that, as the on-ramp volume reaches a certain level, it starts to cause traffic congestion in the mainline traffic. In this case, the CACC vehicles in the general-purpose lane will make active lane changes towards the managed lane. These lane changes will raise intense traffic disturbances that may interrupt the CACC string operation.



**Figure 13. Probability that a CACC vehicle operates in a CACC string (60% CACC with 10800 veh/hr mainline input).**



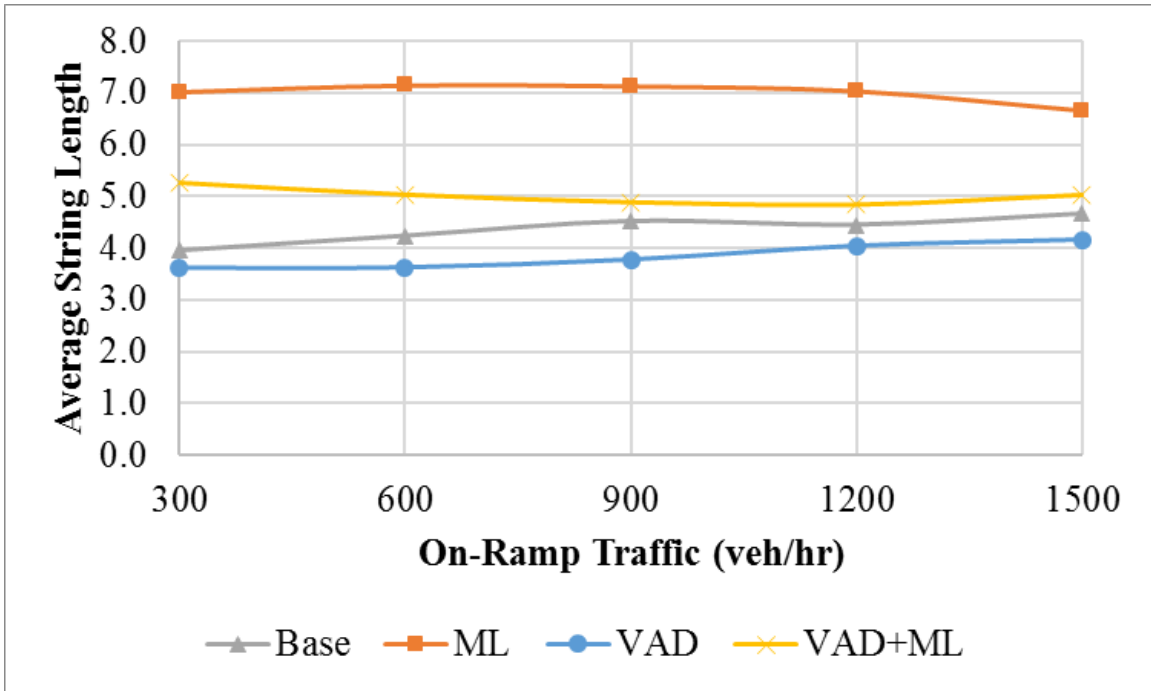


Figure 14. Average CACC vehicle string length (60% CACC with 10800 veh/hr mainline input).

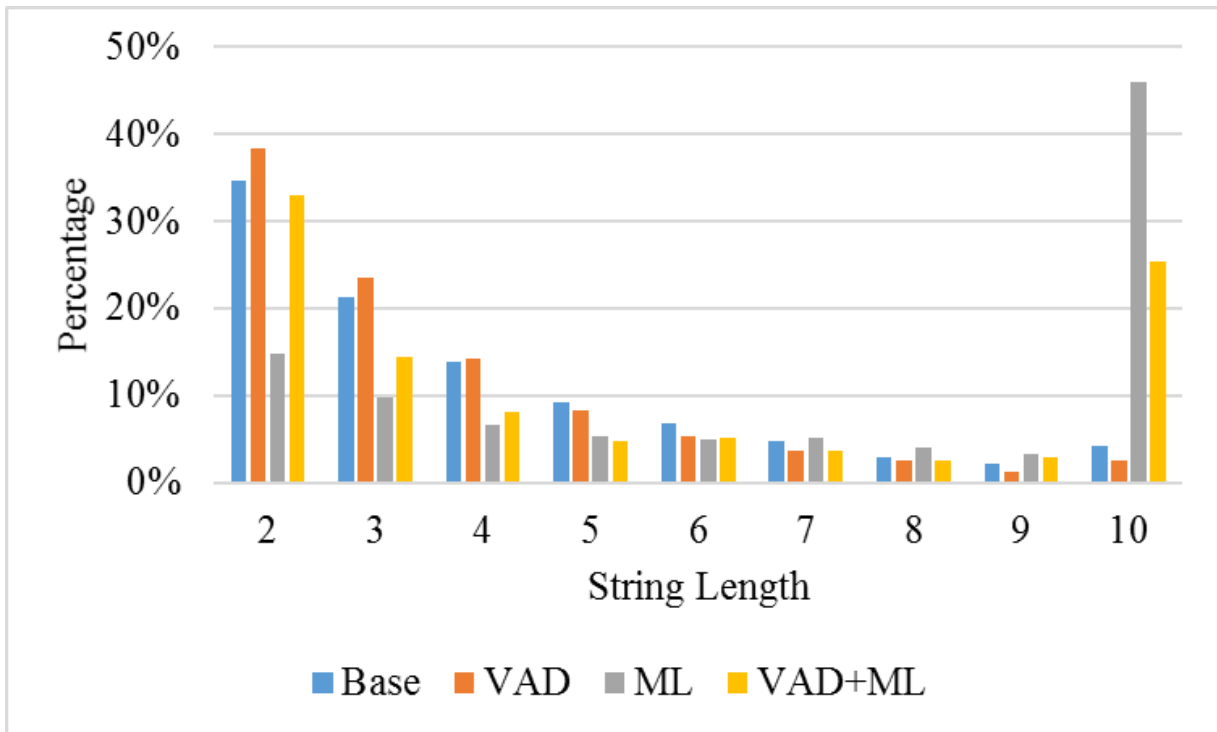
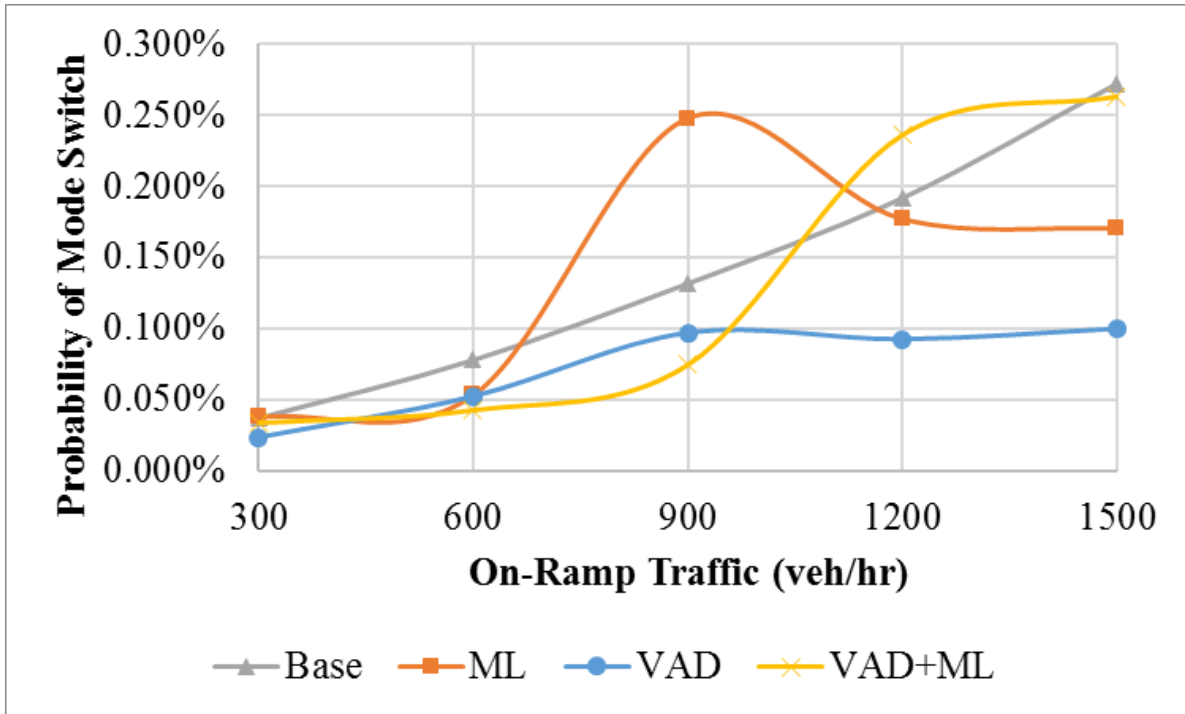


Figure 15. Distribution of string lengths, for maximum allowable length of 10 vehicles (60% CACC with 10800 veh/hr mainline input).



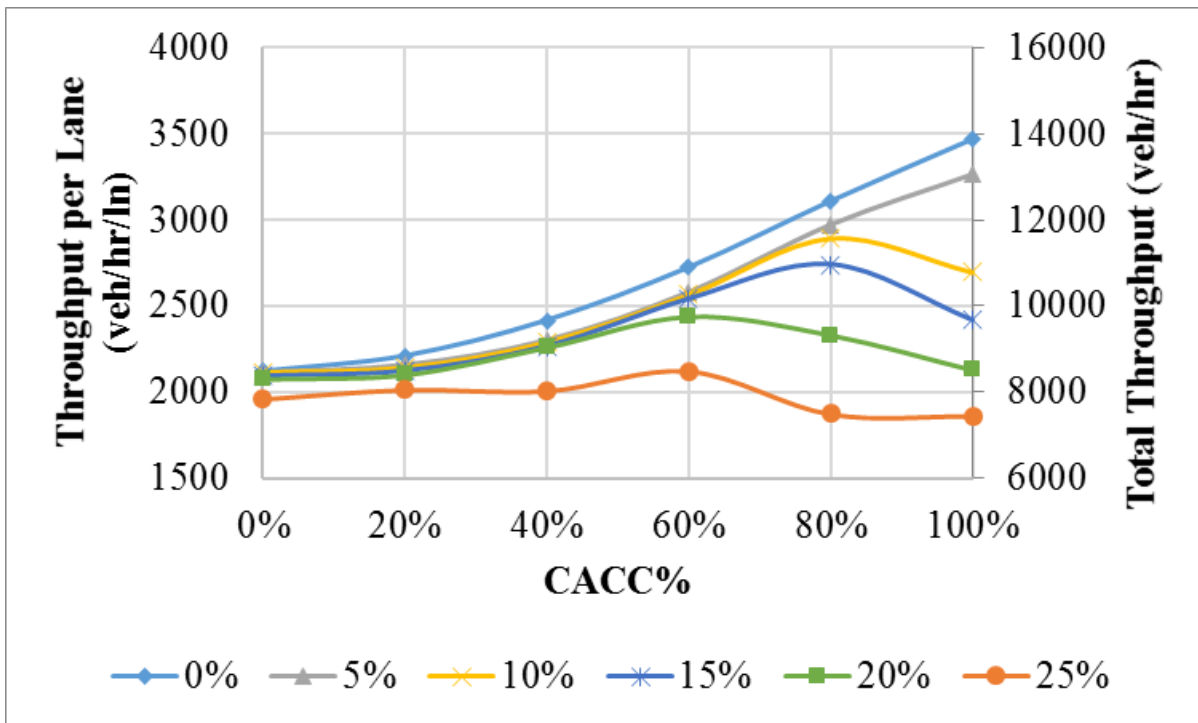
**Figure 16. Probability of mode switch (60% CACC with 10800 veh/hr mainline input).**

### **FREEWAY CAPACITY AT OFF-RAMP BOTTLENECKS**

In this section, we will identify the maximum traffic volume the freeway off-ramp can serve while the freeway mainline remains in the free flow condition. The analysis was performed under various CACC market penetrations and with or without the CACC operation strategies mentioned in the previous section. In the simulation runs, the freeway mainline upstream input equaled the pipeline capacity measured at each CACC market penetration. Then different percentages of the mainline traffic were assumed to exit the freeway through the off-ramp of the study network. The percentage of the mainline flow was used instead of the absolute traffic volume because we expected that the off-ramp traffic should be proportional to the mainline flow. The maximum percentage of the mainline traffic flow that can exit the freeway is called the maximum off-ramp traffic percentage in the remainder of this section.

Figure 17 shows the freeway throughput of the base case. When the CACC market penetration is 60% or lower, up to 20% of the mainline traffic can exit the freeway without causing traffic breakdown. But when the CACC market penetration further increases, the maximum off-ramp traffic percentage decreases significantly. When the CACC penetration is 80%, the percentage is between 15% and 20% and at the 100% CACC case it is only

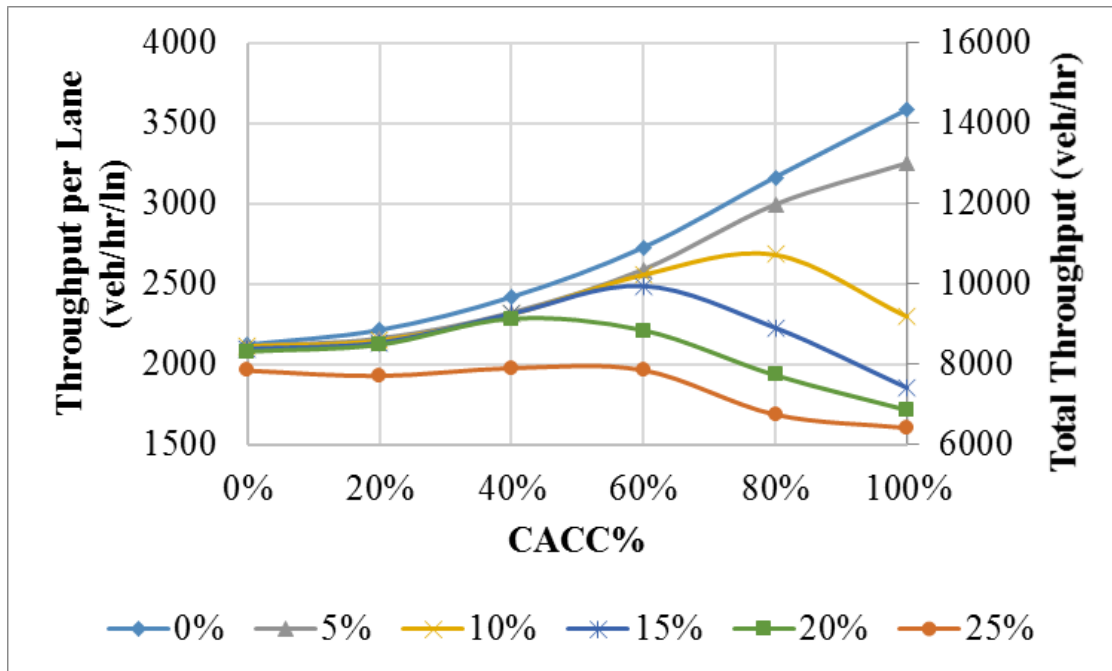
between 5% and 10%. The freeway can serve smaller off-ramp traffic percentages in the higher CACC market penetration cases because the traffic density becomes very large in those cases. It is difficult for vehicles to find acceptable gaps to make discretionary or active lane changes towards the off-ramp lane. As the exiting vehicle is close to the off-ramp but still cannot merge into the off-ramp, the driver must make aggressive mandatory lane changes, which cause strong disturbances to the traffic stream. Such disturbances can easily propagate upstream and develop into heavy shockwaves in the dense traffic flow. In addition, most of the exiting vehicles are CACC vehicles in the high CACC market penetration cases. When a CACC vehicle wants to exit, the driver needs to first turn off the CACC and manually make the lane change. Such a behavior will break the CACC string operation and further negatively impact the throughput.



**Figure 17. Freeway throughput achievable at various off-ramp traffic percentages under the base case.**

As Figure 18 shows, the DLC restriction strategy makes the performance of the off-ramp bottleneck worse. After implementing the strategy, the maximum off-ramp traffic percentage declines when the CACC market penetration is 40% or higher. At the same off-ramp traffic percentage, the throughput is also lower with the DLC restriction strategy. The DLC restriction strategy has a negative impact because it prevents CACC vehicles in the rightmost lane from making discretionary lane changes to the left lanes, even if the rightmost lane is packed with the exiting traffic. In this case, they fail to create gaps for exiting vehicles that are still waiting in the left lanes, trying to find gaps to merge. When those vehicles wait for gaps, they will travel slowly to synchronize their speed to the

rightmost lane. Subsequently, they slow down the upstream vehicles that do not want to exit the freeway and further reduce the freeway throughput.



**Figure 18. Freeway throughput of various off-ramp traffic percentages under the DLC restriction case.**

The ML strategy also decreases the performance of the off-ramp bottleneck (see Figure 19). As the strategy is implemented, the leftmost lane will take more traffic. When those vehicles need to exit the freeway, they make extra lane changing maneuvers, which can cause extra disturbances to the traffic flow. With this strategy, the maximum off-ramp traffic percentage reduces to a level between 5% and 10% under 80% CACC penetration. Under 60% CACC penetration, the maximum off-ramp traffic percentage reduces to a level between 10% and 15%. When the CACC market penetration is 40%, the ML strategy does not significantly reduce the throughput of the off-ramp area.

The VAD strategy can slightly improve the throughput when the off-ramp traffic does not exceed the maximum off-ramp traffic percentage (see Figure 20). Once the off-ramp traffic becomes larger than the maximum percentage, the throughput is smaller under the 60% and 80% CACC market penetration cases. The level of the maximum off-ramp traffic percentage is the same with and without the VAD strategy.

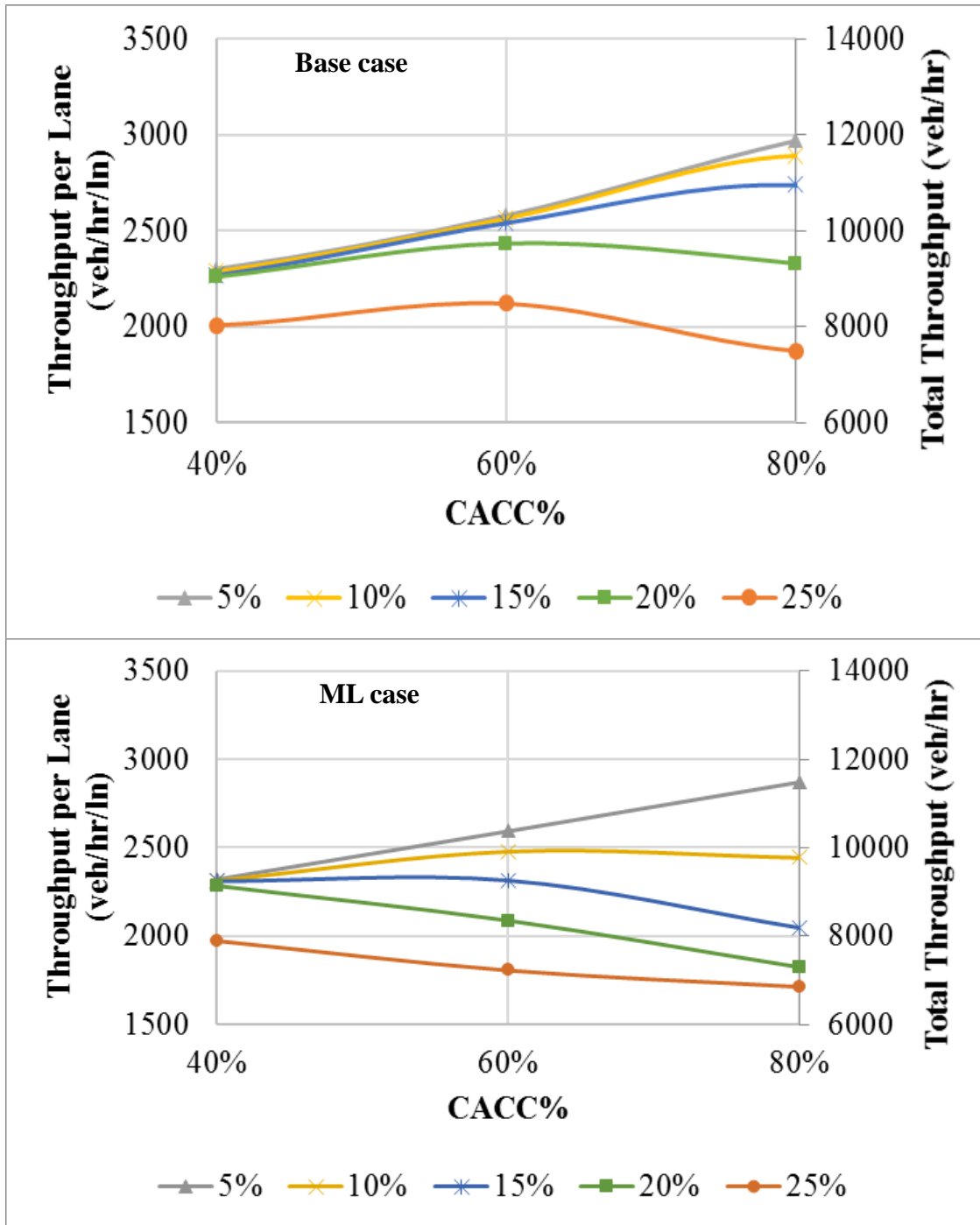


Figure 19. Freeway throughput with various off-ramp traffic percentages, base case vs. managed lane case.

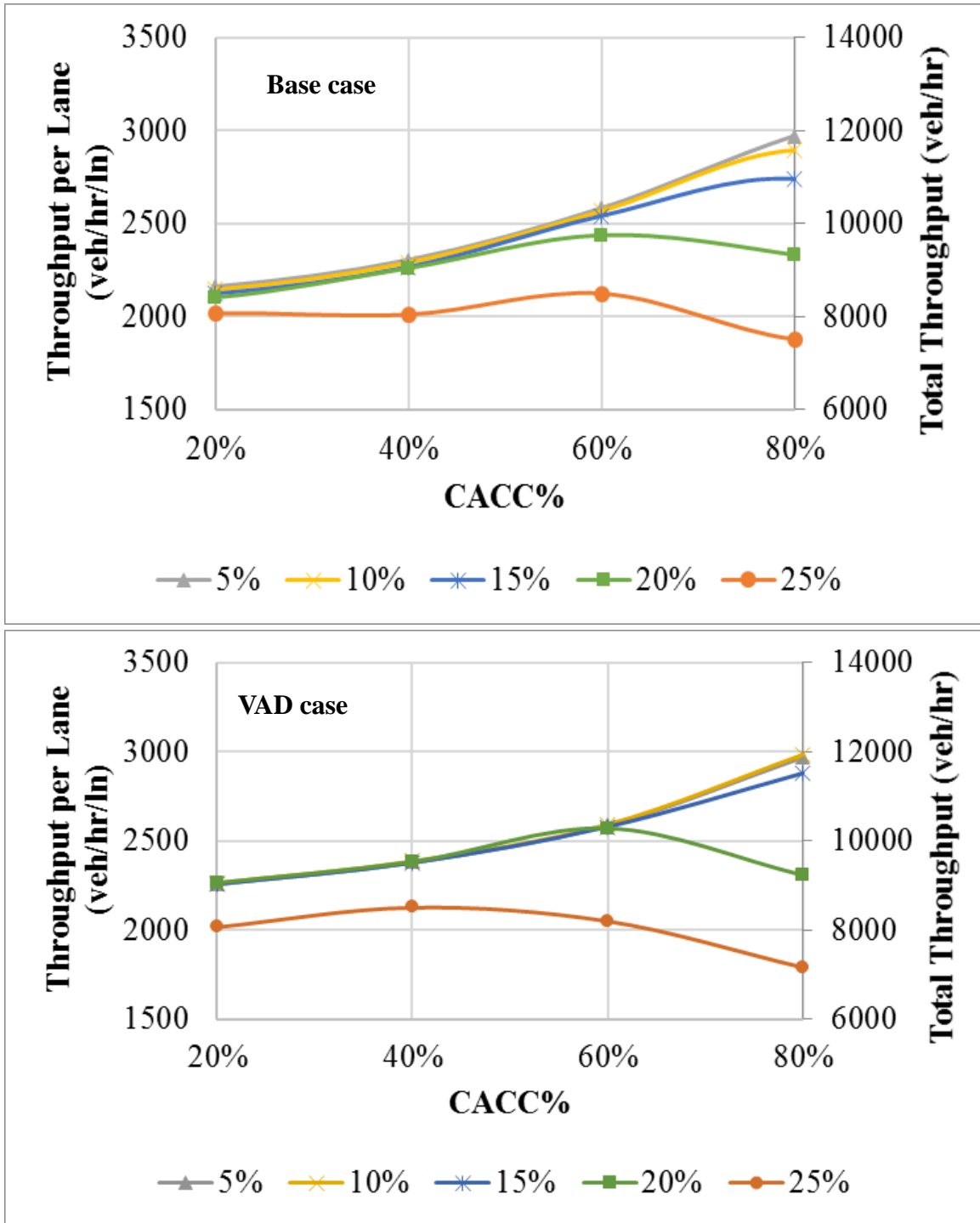
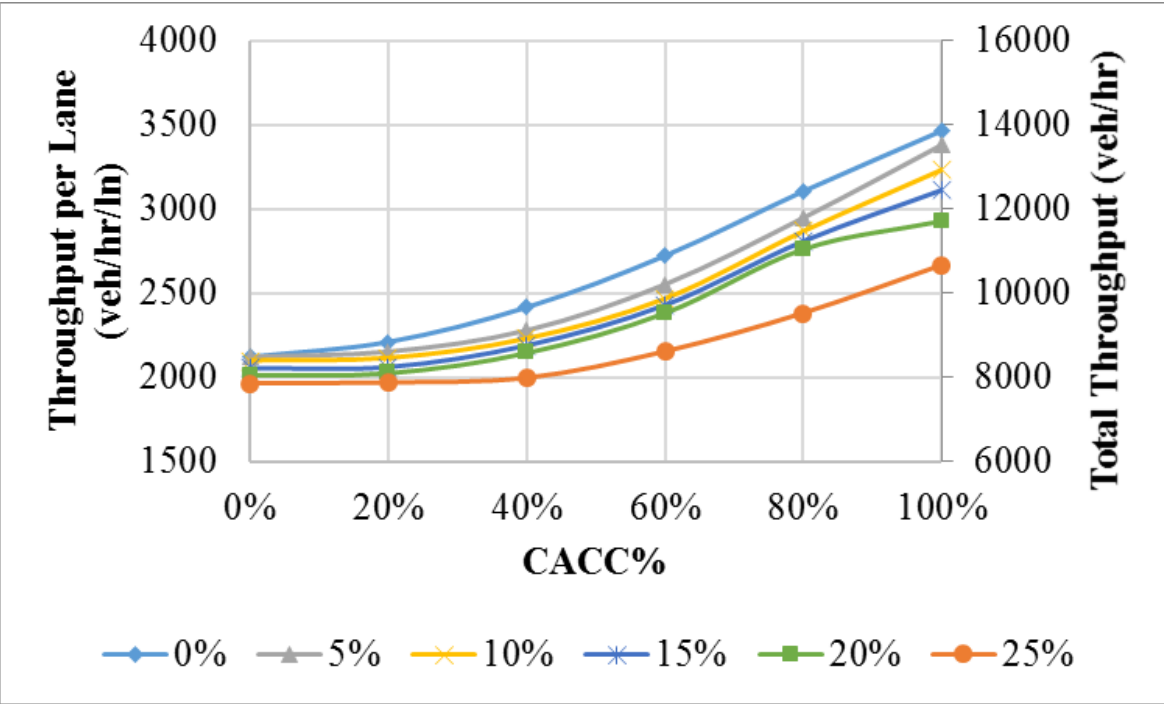


Figure 20. Freeway throughput with various off-ramp traffic percentages, base case vs. VAD case.

The above analysis shows that the freeway off-ramp area may become a major bottleneck as the off-ramp volume increases due to the increase of the freeway throughput with the CACC market penetration. The traffic management strategies that increase the capacity and throughput for the basic freeway segments and merge areas may reduce the performance of the off-ramp area. To improve the operation, we can recommend drivers to start making lane changes towards the freeway exit earlier than they normally do. In this case, most them can make discretionary or active lane changes instead of aggressive mandatory lane changes before the exit. As the number of mandatory lane changes reduces, the severe disturbances in the traffic stream also decrease. In addition, we can keep the CACC vehicle in the CACC mode if the driver cannot find an acceptable gap in the target lane when he is trying to perform the discretionary or active lane changes towards the exit. In this case, we reduce the number of mode switches for the CACC drivers and thereby lower the probability that the CACC string operation is interrupted.

The above improvement strategy has been implemented in the simulation. Before the improvement, the exiting drivers would start searching for gaps in the right lane 1.5 kilometers upstream from the off-ramp. With the improvement, the drivers start the lane change process 3 kilometers upstream. The results for the improvement strategy are shown in Figure 21. The traffic improves significantly. At 100% CACC penetration, the maximum off-ramp traffic percentage increases to a level between 15% and 20%. The throughput reduction after the off-ramp traffic exceeds the maximum percentage also becomes much smaller.

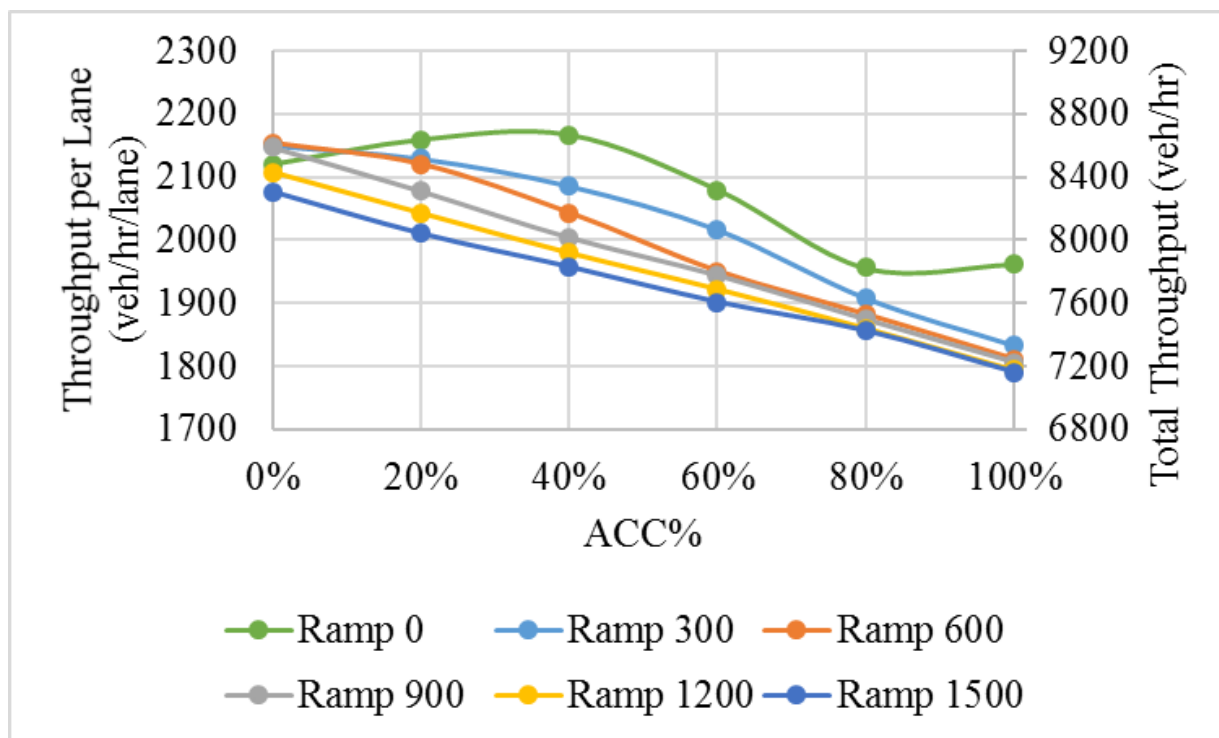


**Figure 21. Freeway throughput of various off-ramp traffic percentages under off-ramp bottleneck improvement strategy of earlier lane changing by exiting vehicles.**

## IMPACT OF ACC OPERATION ON TRAFFIC FLOW

In addition to the impact analysis for the CACC vehicle operation, we have examined the capacity and throughput for the simple network under various ACC market penetrations. We applied the same simulation experiment setup for the ACC study as we performed the CACC studies. The simulation network is the simple network shown in Figure 1. In addition to the pipeline capacity analysis, we also investigated the freeway throughput for the on-ramp bottleneck and the off-ramp bottleneck.

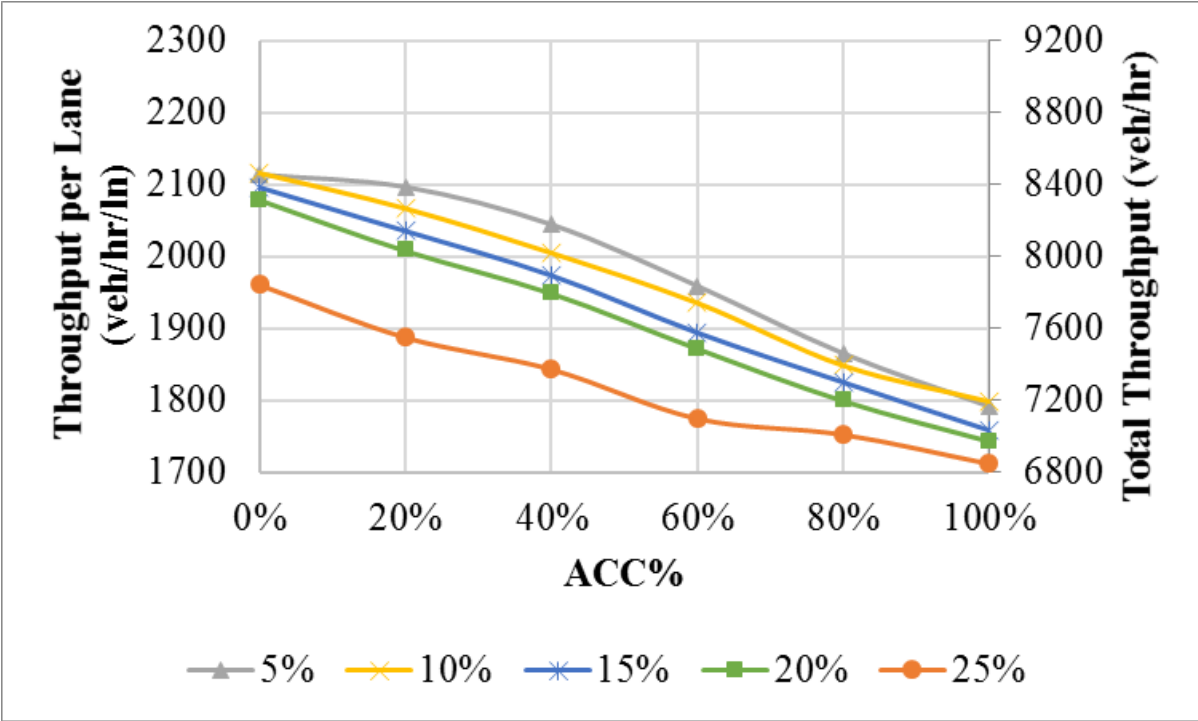
The pipeline capacity and freeway throughput under various ACC market penetrations are depicted in Figure 22. Because the ACC operation decreases the stability of the traffic flow, we observe a decrease trend of the pipeline capacity as the ACC market penetration increases. We also observe a linear decrease trend of the throughput with the ACC market penetration, regardless of the on-ramp input. Especially when the ACC market penetration is 100%, the throughput will have a significant decrease although the on-ramp input is very small. It indicates that the traffic stream under 100% ACC is unstable. A minor disturbance from the on-ramp can cause the traffic breakdown, and subsequently lead to a queue discharging flow of 1800 vehicles per hour per lane.



**Figure 22. Freeway throughput with ACC at multiple market penetrations with various on-ramp traffic inputs (veh/hr/ln).**



The ACC operation can negatively impact the operation of the off-ramp bottleneck as well. As the ACC market penetration increases, the freeway throughput at the off-ramp area also reduces linearly, regardless of the percentage of the off-ramp traffic (see Figure 23). The analysis results indicate that the implementation of ACC without V2V cooperation cannot improve the overall performance of the freeway.



**Figure 23. Freeway throughput with ACC at different market penetrations and various off-ramp traffic percentages.**

**RECOMMENDED CACC OPERATIONAL ALTERNATIVES FOR CORRIDOR IMPLEMENTATION**

Based on the previous discussion, we have the following recommendations regarding the implementation of the traffic management strategies for analyses in the larger SR-99 network:

- The VAD strategy can improve the traffic operation for the basic freeway segments, on-ramp merging areas, and off-ramp diverging areas. It increases the probability that a CACC vehicle operates in a CACC string and reduces the probability that a CACC driver turns off the CACC mode. For these reasons, this strategy is recommended for implementation in the large network.

- The ML strategy can be applied when the CACC market penetration is between 40% and 80%. It can improve the capacity and throughput for the basic freeway segments and on-ramp areas, although its influence becomes smaller as the CACC market penetration increases. However, it can negatively impact the performance of the off-ramp area when the CACC market penetration is 60% or larger. Therefore, we will use the ML strategy only under the 40% CACC market penetration in the SR-99 network.
- Since we will use the current traffic demand as the input for the SR-99 analysis, the off-ramp traffic should not cause heavy traffic congestion, regardless of the increase of the CACC market penetration. For example, the highest off-ramp traffic percentage is about 15% at the Stockton Blvd. off-ramp in the middle of the corridor. In this case, the traffic management for the off-ramp bottleneck will not be used.

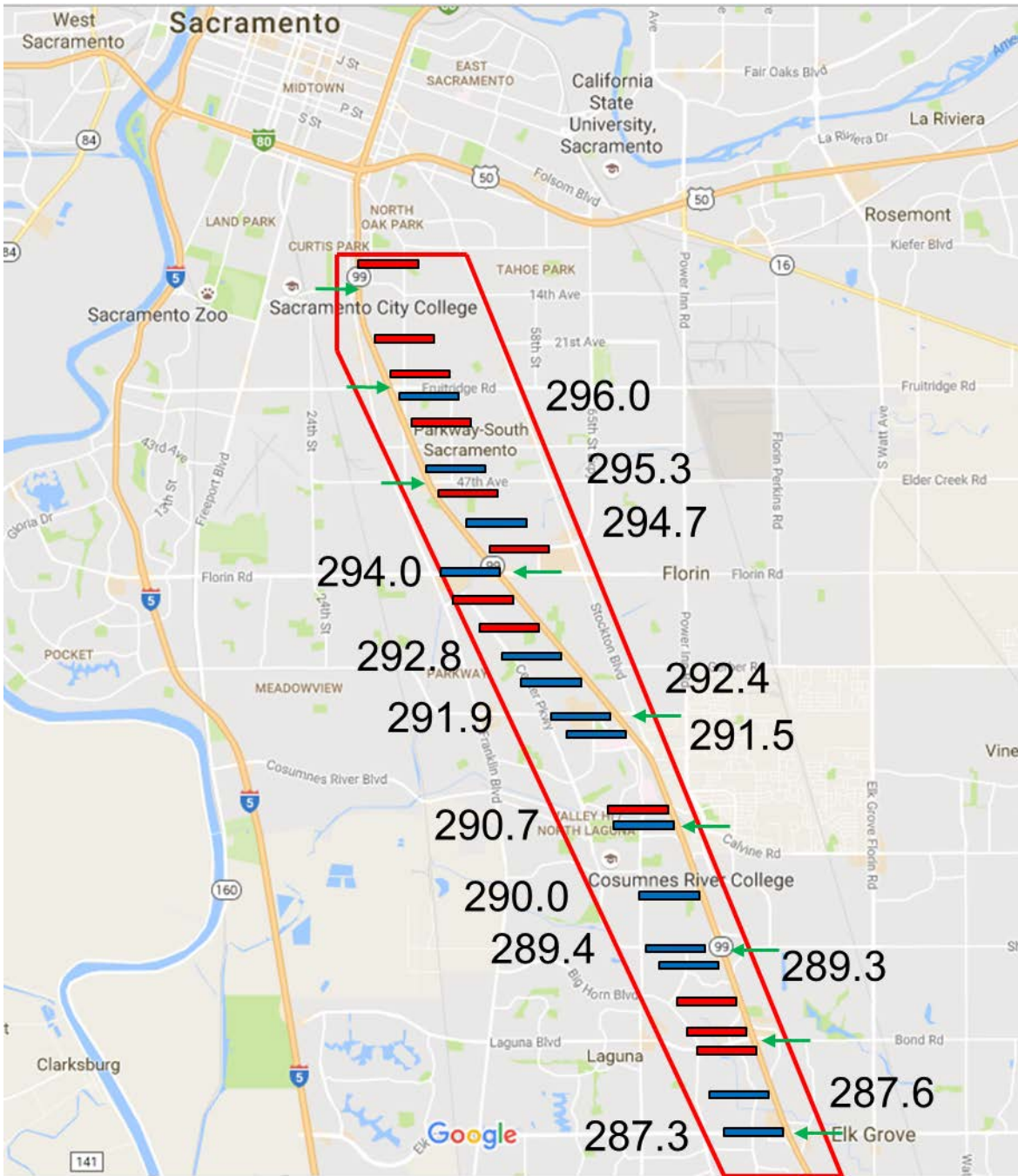
## **IMPACT OF CACC OPERATION ON SR-99 FREEWAY CORRIDOR**

### **DESCRIPTION OF THE STUDY NETWORK**

State Route (SR) 99 northbound was selected for the corridor study. This section of freeway spans from the Elk Grove Blvd. interchange to the US-50 freeway interchange south of downtown Sacramento, CA. As indicated by the arrows in Figure 24, there are 9 interchanges with local arterial streets (green arrows in Figure 24): 4 partial cloverleaf interchanges, 3 full cloverleaf interchanges, and 2 diamond interchanges with the local arterials. Furthermore, there are 3 lanes (one high occupancy vehicle or HOV lane and two general purpose lanes) in each direction upstream of the Calvine Road interchange while an additional general purpose lane is added downstream of that interchange. The on-ramp merging and weaving sections located downstream of the Elk Grove Blvd. interchange, as well as the off-ramp at the US-50 freeway interchange, contribute to the morning peak recurrent delay observed in this corridor. This peak period typically begins at 6:30 AM and ends around 9:00 AM, and the morning congestion pattern exhibits the typical peak period when there is high demand for suburb to downtown trips during the morning hours. There is a wide coverage of detectors throughout the corridor. Detectors with good data quality are shown in blue, those with less acceptable data quality, shown in red, were not used to collect field data for calibration and validation. We also implemented detectors in the simulation network. Data from those detectors were used to construct speed contour plot to help demonstrate the overall traffic flow dynamics of the corridor. Currently, the on-ramps are metered using the local traffic responsive demand-capacity approach to control the flow of on-ramp traffic and mitigate the peak hour congestion.

### **ANALYSIS SCENARIOS AND PERFORMANCE MEASURES**

The traffic flow dynamics of the SR-99 corridor were compared under 0%, 20%, 40%, 60%, 80% and 100% CACC market penetration. Under the low CACC market penetrations, we also examined the differences with and without the VAD and ML strategies. The traffic demand input was obtained from the field observations and it was the same for all the scenarios. The simulation period was an 8-hour period from 4:00 am to 12:00 pm. The total vehicle miles traveled (VMT), total vehicle time traveled (VTT), and average space mean speed were used for measuring the mobility performance of each scenario. To compute the average space mean speed, the space mean speed of the entire corridor was observed every 5 minutes in a simulation run. The measured speed data were the basis to compute the average speed. There were 5 simulation replications for each scenario. The performance measures were estimated based on the averaged data of those replications.



**Figure 24. Study site: SR-99 freeway south of downtown Sacramento, CA, with detector stations and post-miles identified.**

## MOBILITY PERFORMANCE UNDER VARIOUS CACC MARKET PENETRATIONS

Figure 25 shows the total VMT and VTT of the corridor. Since the demand input is the same for all the scenarios and the origin and destination for each vehicle is determined based on the observed OD matrix, the route of the simulated vehicles in each scenario is also the same. In this case, the total VMT has little change with the CACC market penetration. There is a minor increase of the VMT when the CACC market penetration rises from 80% to 100%. Note the total vehicle input for the 8-hour simulation period is about 76600 vehicles. The average VMT increase per vehicle is only about 40 meters, which can be attributed to the extra lane changes the drivers make towards the faster lanes. The total VTT decreases significantly as the CACC market penetration increases. It indicates that the traffic flow becomes less congested when there are more CACC vehicles in the traffic stream. We can also observe a rapid decrease of VTT when the CACC market penetration increases from 20% to 40%. In comparison, the total VTT is almost the same between 0% and 20% CACC market penetrations. It suggests that the CACC vehicle string operation cannot change the traffic flow pattern in this corridor until the CACC market penetration reaches a level between 20% and 40%. The space mean speed shown in Figure 26 has the same trend as the total VTT. As the CACC market penetration increases, the speed of the corridor also increases significantly.

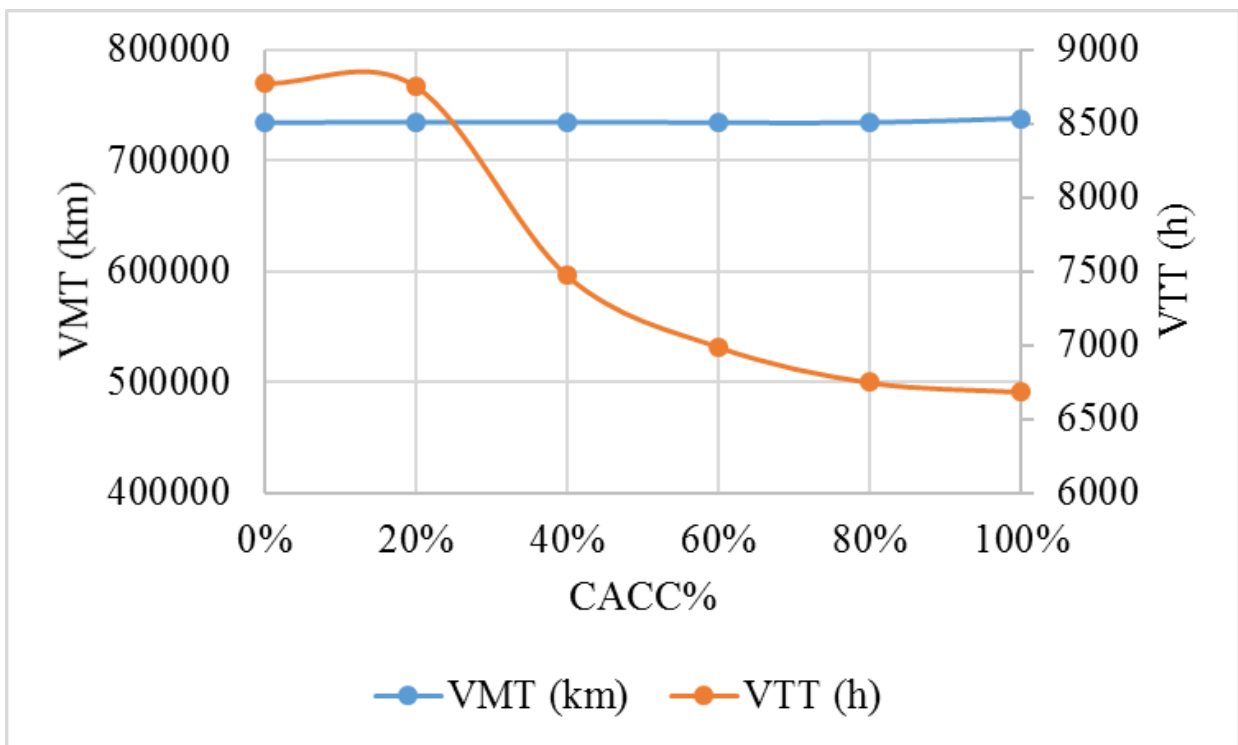
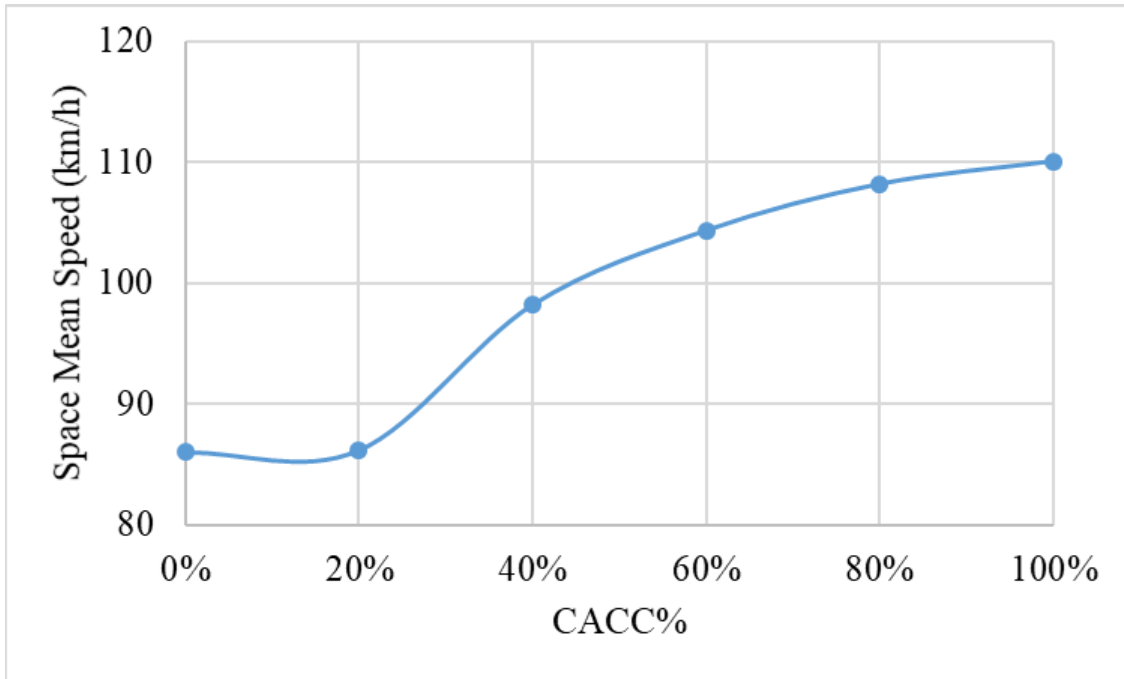
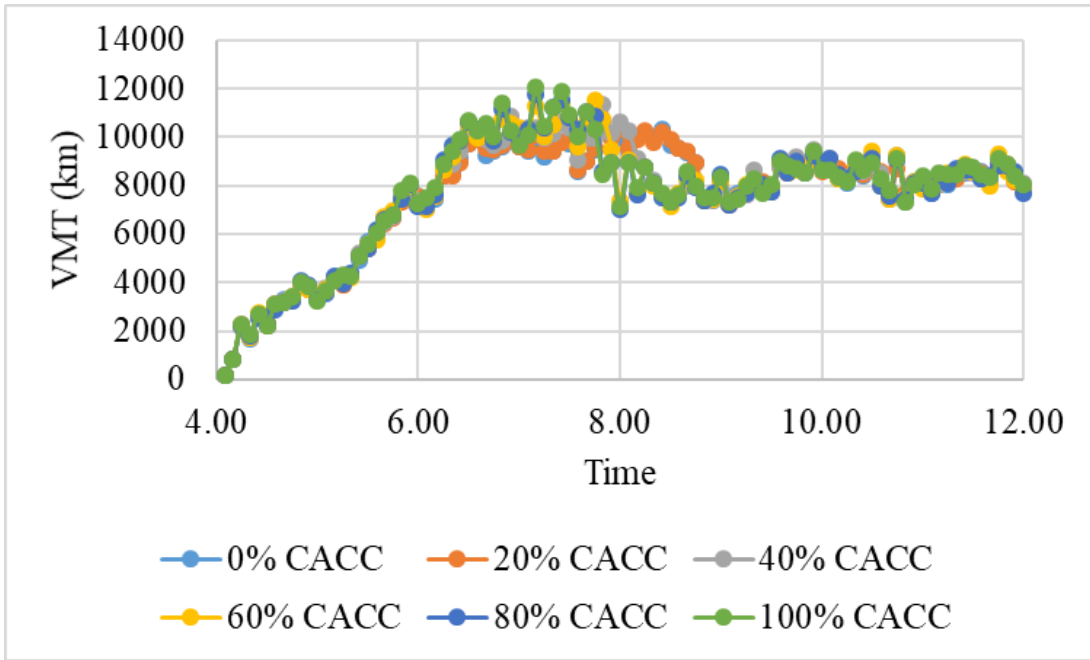


Figure 25. Total VMT and VTT for SR-99 Corridor with CACC.

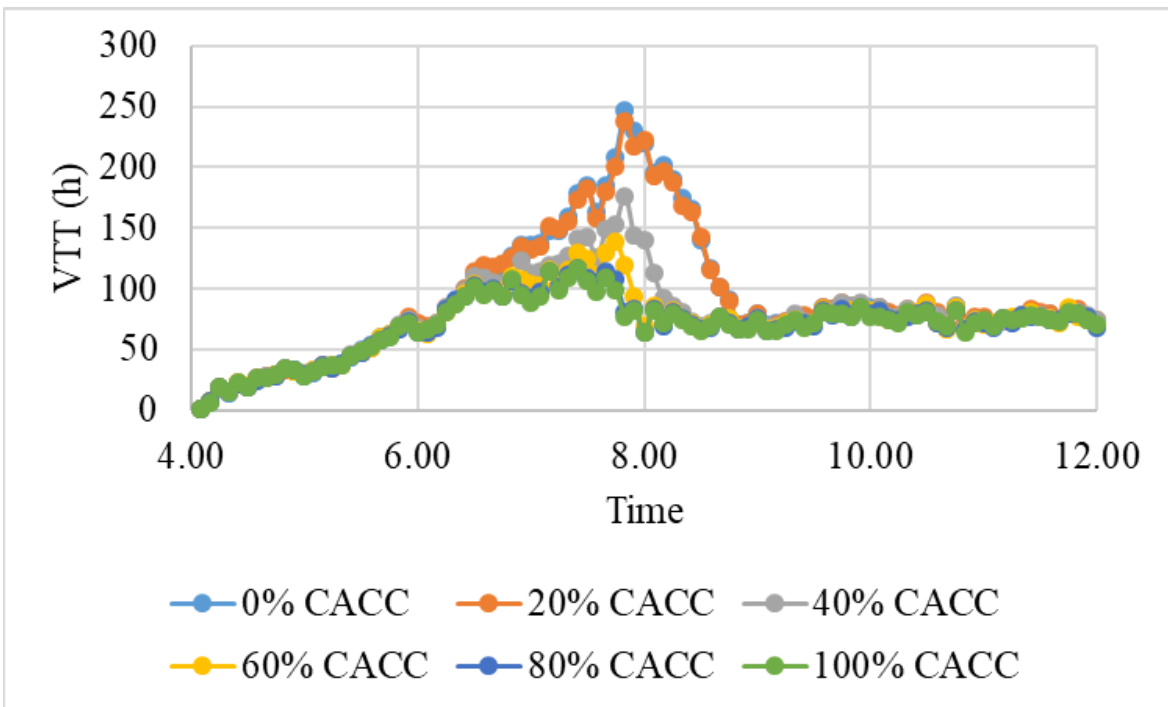


**Figure 26. Average space mean speed for SR-99 corridor with CACC.**

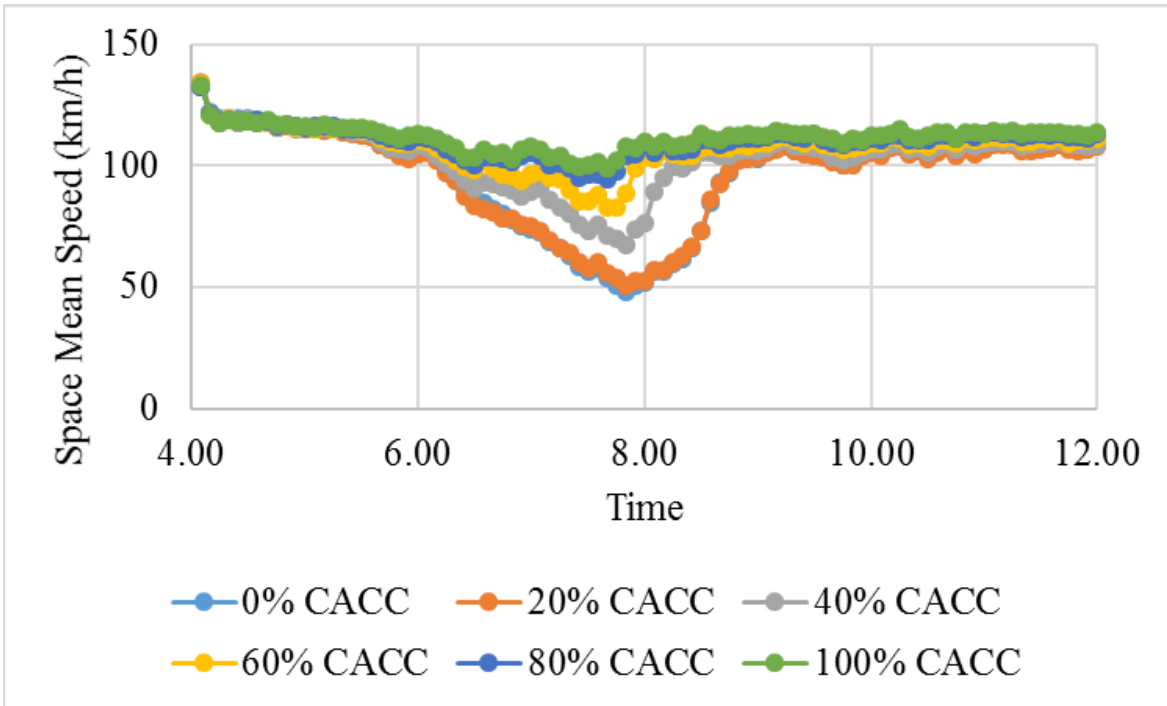
Based on the following time series plots (Figures 27-29), we can also identify that the CACC vehicle string operation has the most significant impact during the peak hours. The VTT has a substantial decrease and the space mean speed has a great increase during the morning peak. Under the high CACC market penetration, the space mean speed is almost the same during the peak hours and after the peak hours. It indicates the great improvement of the traffic flow due to the application of the CACC.



**Figure 27. Time series of VMT (VMT data measured at each 5 minutes) for SR-99 corridor at different CACC market penetrations.**



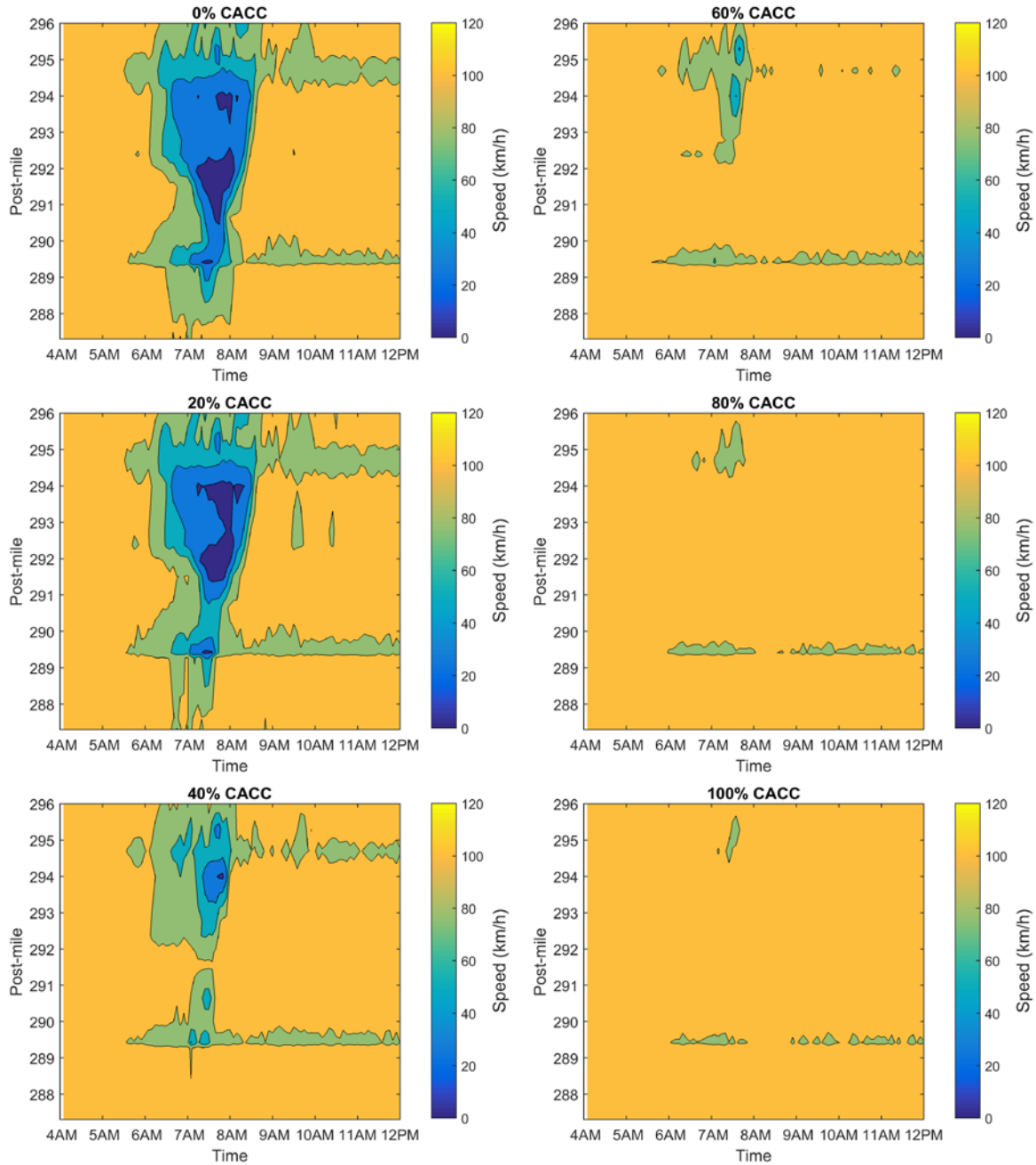
**Figure 28. Time series of VTT (VTT data measured at each 5 minutes) for SR-99 corridor at different CACC market penetrations.**



**Figure 29. Time series of average space mean speed (speed data measured at each 5 minutes) for SR-99 corridor at different CACC market penetrations.**

The speed contour plot of Figure 30 also suggests the same observation: the traffic flow is greatly improved when the CACC market penetration is 40% or higher. Since there is little improvement at the 20% CACC case, we will examine if we can increase the mobility performance for this case via the CACC operation strategies.

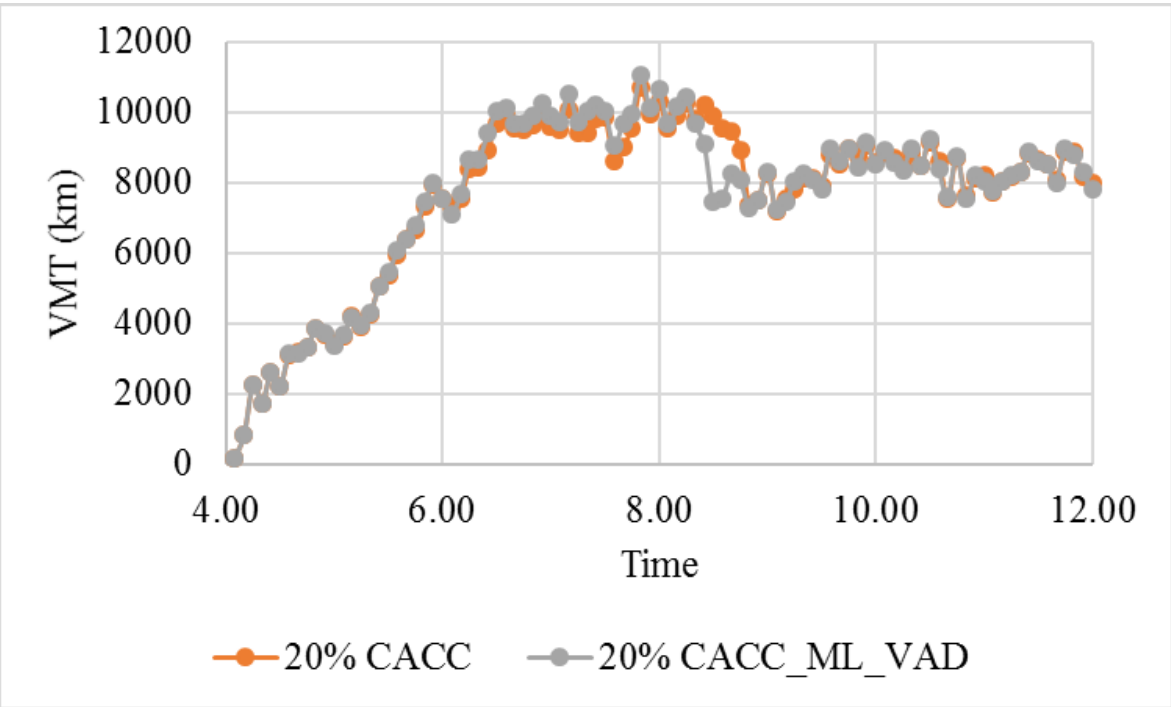




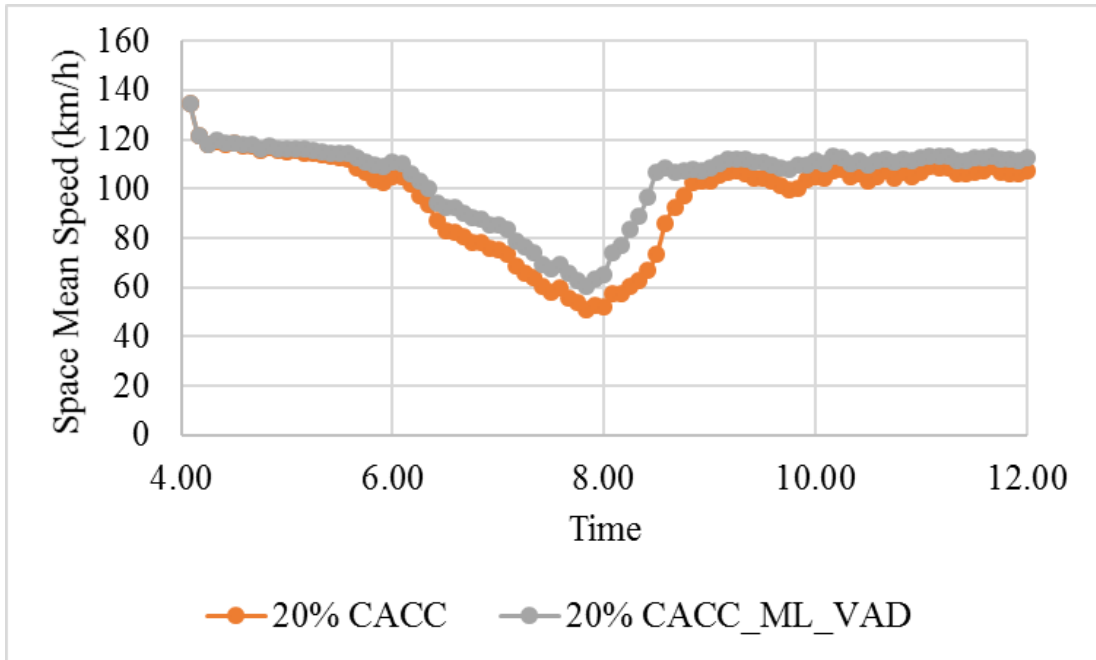
**Figure 30. Speed contour plots for SR-99 corridor for each CACC market penetration.**

The ML and VAD strategies were implemented under the 20% CACC market penetration case. The changes of VMT, VTT and space mean speed after deploying these management strategies are demonstrated in Figures 31 to 33. The total VMT between the two cases is not substantially different (i.e., 735114 kilometers without the operation strategies and 735724 kilometers with the operation strategies). But Figure 31 suggests that the VMT time series have distinct patterns. Without the CACC operation strategy, the traffic was

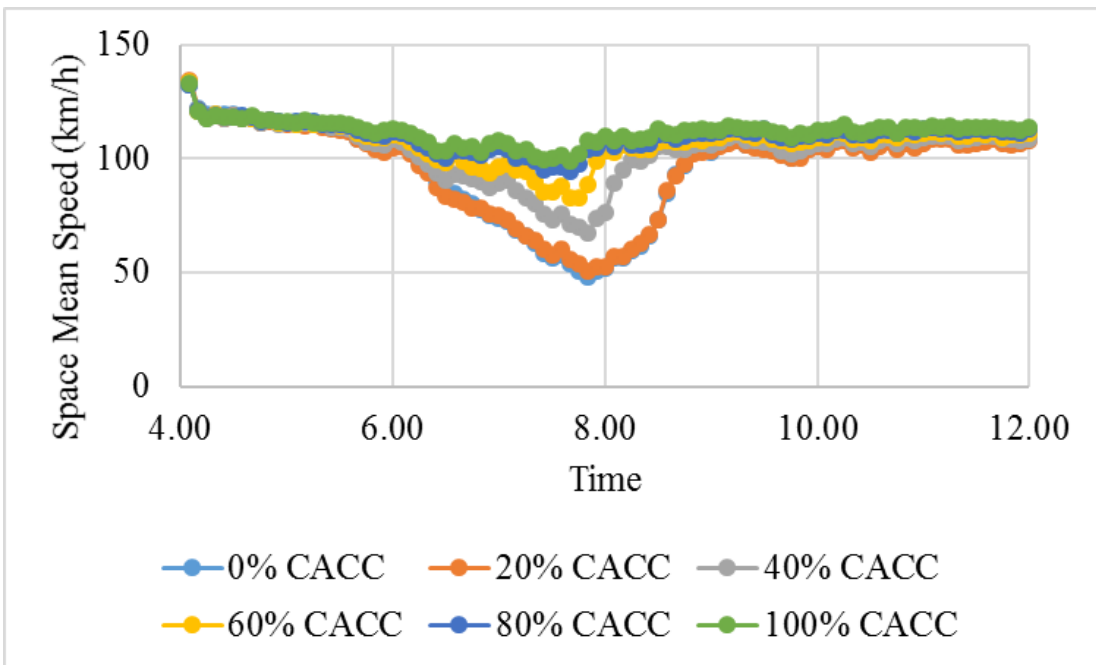
congested during the peak hours (e.g., from 6:00 to 8:30 am) and many vehicles waited in queues during the period. The queued vehicles contributed a great amount of VMT as the traffic congestion dissipated between 8:30 to 9:00 am. With these strategies, the traffic was not heavily congested and more vehicles could travel through the corridor during the peak hours, leading to a higher VMT curve from 6:00 to 8:30 am. Since there were not many queued vehicles, the VMT between 8:30 to 9:00 am was smaller than the previous case. Figures 32 and 33 show that the operation strategies can decrease the total vehicle time traveled and increase the space mean speed for the peak hours. The mobility improvement due to these operational strategies can also be depicted by the speed contour plots (Figure 34). We can easily identify that the strategies can help both decrease the duration and the intensity of the traffic congestion at individual bottlenecks of the corridor.



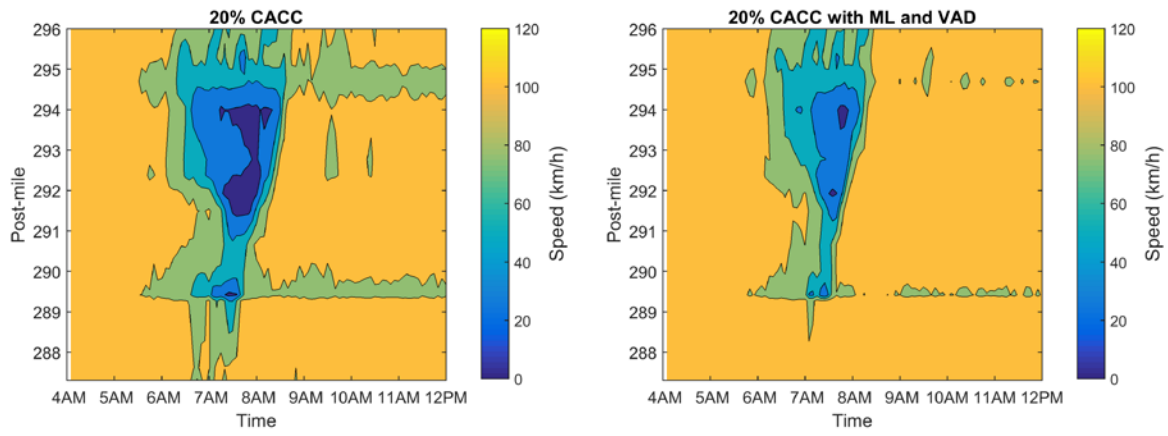
**Figure 31. Time series of VMT at 20% CACC market penetration (VMT data measured at 5 minute intervals).**



**Figure 32. Time series of VTT at 20% CACC market penetration (VTT data measured at 5 minute intervals).**



**Figure 33. Time series of average space mean speed at 20% CACC market penetration (speed data measured at 5 minute intervals).**



**Figure 34. Speed contour plots for 20% CACC market penetration (base case and with ML and VAD strategies).**

## CONCLUSIONS

In this research, we have explored the impact of CACC vehicle string operations on freeway mobility performance. In particular, we have examined the influence of CACC operation strategies in terms of improving the probability of forming and maintaining CACC vehicle strings in the traffic stream, and subsequently increasing the freeway capacity and throughput. For the basic freeway segment, our analysis results indicate a quadratic increase trend of the pipeline capacity with the CACC market penetration. At 100% market penetration, the freeway capacity is roughly 63% higher than at 0% market penetration. The ML and VAD strategy are most helpful under the low and medium CACC market penetrations (e.g., 20% to 60%) as they increase the probability for a CACC vehicle to operate in a CACC string. In addition, the ML strategy can greatly increase the average CACC string length in the managed lane. Under the high CACC market penetrations (e.g., 80% to 100%), the CACC strings are frequently interrupted by the discretionary lane change behaviors of vehicles within the string. In this case, the DLC restriction strategy has the most significant influence.

In the freeway on-ramp merging area, the throughput also increases quadratically with the CACC market penetration, although the improvement decreases substantially as the on-ramp traffic increases. The ML and VAD strategy can greatly change the traffic patterns of the merging area, and thus improve the traffic flow of the merge bottleneck. The ML strategy makes CACC vehicles concentrate in the managed lane, leading to a high output flow of the lane even when the on-ramp traffic is large. As the CACC vehicles move to the managed lane, the traffic flow in the rightmost lane becomes lighter. The on-ramp vehicles can find gaps in the rightmost lane more easily. With the VAD strategy, the on-ramp CACC vehicles can find a string leader as soon as they merge into the freeway mainline. Those vehicles can dispatch from the merging area more quickly when operating in the CACC string. After implementing the ML and VAD strategy at the same time, the throughput can be further increased, especially under high on-ramp input cases.

The traffic flow in the off-ramp area is expected to become worse if the off-ramp traffic flow increases proportionally with the mainline traffic as the CACC market penetration grows. The ML strategy may further degrade the throughput of the off-ramp area because of the disturbances caused by vehicles in the managed lane as they make lane changes towards the off-ramp. To improve the mobility performance of the off-ramp area, we have tested a strategy that offers early lane change advisory messages to the exiting vehicles. With this strategy, drivers will start making lane changes towards the exit at a further distance than they normally do. In this case, the aggressive lane changes performed by the exiting drivers near the end of the off-ramp can be greatly reduced. The analysis results show that the strategy can eliminate the off-ramp bottleneck when the off-ramp traffic is 20% of the mainline traffic or lower.

The traffic conditions for the SR-99 network improve significantly with the CACC market penetration. We have identified a critical CACC market penetration between 20% and 40%. Before the critical market penetration, the traffic flow dynamics are almost the same, regardless of the percentage of CACC vehicles in the traffic flow. When the CACC market

penetration is higher than the critical level, the mobility performance improves rapidly. The critical CACC market penetration level can be further lowered by implementing the CACC operation strategies. After the ML and VAD strategy were implemented for the 20% CACC market penetration case, the VTT and space mean speed had significant improvements. It suggests that we can achieve high freeway mobility with proper CACC operation strategies even when there are only a few vehicles equipped with CACC.

In the future, we recommend continuing the research by considering higher level coordination strategies that help CACC vehicles form strings based on their routes. In addition, as the CACC market penetration increases, it is unlikely that CACC is the only advanced traffic technology implemented. Systems such as automated merging or lane changing assistance, and speed harmonization could be deployed together with CACC. For this reason, we also recommend exploring the impacts of those systems on the CACC vehicle string operations. In our current model, we have made several assumptions regarding CACC vehicles' lane changing behaviors because there is no empirical data to develop a specific lane changing model for them. As more field tests are performed to determine the car-following and lane-changing behaviors of CACC drivers, we recommend continuing to update the CACC simulation models based on the field data.

## REFERENCES

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Neudorff, L. G., Randall, J. E., Reiss, R., & Gordon, R. (2003). *Freeway management and operations handbook* (No. FHWA-OP-04-003).