# COLLABORATIVE MERGING BEHAVIORS AND THEIR IMPACTS ON FREEWAY RAMP OPERATIONS UNDER CONNECTED VEHICLE ENVIRONMENT

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## ABSTRACT

Under connected vehicle environment, vehicles are able to communicate and exchange detailed information such as speed, acceleration, and position in real time. Such information is important for improving traffic safety. In the meantime, it allows vehicles to collaborate with each other, which may significantly improve traffic operations particularly at intersections and freeway ramps. To assess the potential benefits of collaborative driving behaviors enabled by connected vehicle technologies, this research proposes an optimization-based ramp control strategy and develops a simulation platform using VISSIM, MATLAB, and the Car2X module in VISSIM. In addition to the optimal control strategy, an empirical gradual speed limit control strategy is also proposed. These strategies are evaluated using the developed simulation platform in terms of average speed, average delay time, and throughput and are compared with a benchmark case with no control. The study results indicate that the proposed optimal control strategy can effectively coordinate all merging vehicles at freeway on-ramps and substantially improve safety and efficiency, especially when the freeway traffic is not oversaturated.

**Keywords:** Connected vehicle, driver behavior, autonomous driving, ramp control, MATLAB, optimization, VISSIM, Car2X

## 1. INTRODUCTION

In freeway ramp areas, frequent lane-changing and merging maneuvers can significantly reduce capacity and cause traffic congestion. These maneuvers may also jeopardize traffic safety, especially when vehicles from on-ramps have to first decelerate to a low speed due to congestion or lack of safe gaps, merge onto the freeway, and accelerate to normal speeds. Under connected vehicle environment, vehicles are able to communicate and exchange detailed information such as speed, acceleration, and position in real time. Such information is important for improving traffic safety. In the meantime, it allows vehicles to collaborate with each other, which may significantly improve traffic operations particularly at intersections and freeway ramps. Such collaborations can be facilitated by autonomous vehicles as they require only a minimum "reaction time". Additionally, such information can be shared with upstream vehicles in a timely fashion. In this way, they can take proactive actions such as moving to the median or to the left-most lane to make room for the merging ramp vehicles. Intuitively, these collaborative driving behaviors may contribute to smoother merging maneuvers and improved operations in freeway ramp areas.

Recently, many studies [1,2,3,4] have been conducted to investigate the potential benefits that connected vehicle technologies may bring. Most of these studies are focused on intelligent vehicle and traffic control, traffic safety, advanced traveler information systems, and incident management. As an important aspect of intelligent traffic control, ramp control has also been addressed in several of these studies that are summarized below.

Sivaraman and Trivedi [5] investigated active traffic safety based on predictive driver assistance (PDA) and cooperation among vehicles, drivers, and infrastructure. Four levels of cooperation strategies were considered, which were in-vehicle cooperation, vehicle-driver cooperation, Vehicles to Vehicles (V2V) cooperation, and Vehicles to Infrastructure (V2I) cooperation. The authors used Markov Chain Monte Carlo (MCMC) simulation to quantify the safety effects of PDA and cooperation at various levels based on a predefined near-collision scenario. Four cases consisting of one ramp vehicle merging onto a highway were simulated and analyzed. The results show that active safety was greatly enhanced by either one of the PDA, V2V, or V2I strategies.

Shingde et al. [6] proposed and implemented two algorithms called Head of the Lane (HoL) and All Feasible Sequences (AFS) for automated merge control. The HoL is a distributed and iterative merge control algorithm. In each iteration, two vehicles closest to the merging point from the two merging approaches follow certain rules to determine their merge sequence. The AFS is a centralized algorithm. Instead of using an iterative approach, it takes a snapshot of all vehicles from the two merging approaches and determines their merge sequence simultaneously. Experimental results suggest that HoL and AFS perform equally well in terms of average Driving Time To Intersection (DTTI). HoL works only when the traffic volume is low, while AFS works for both low and high traffic conditions.

Milanés et al. [7] developed a ramp control system consisting of a control model and a fuzzy controller. The control model determines when a merging vehicle should enter the main road. The fuzzy controller is used to "drive" all vehicles following the decisions made by the control model. This system was first tested using a simulator. It was further validated in the real world using three vehicles. The real-world validation considered a congested scenario with two closely spaced vehicles on the main road and the third vehicle on the minor road. Lu and Hedrick [8] also developed a mathematical approach for modeling one vehicle from the minor road merging onto the main road between two vehicles. Although these developed methods worked for the simple scenario with only 3 vehicles, it is unclear whether they can effectively and safely handle more complicated scenarios with multiple merging vehicles.

Cao et al. [9] proposed a nonlinear model predictive control (MPC) method for merging traffic control. Only two vehicles were considered in their model and case studies, with one on the main road and the other one on the minor road. This merge control problem was formulated as a nonlinear optimization problem and solved by C/GMRES. Similar to previous studies on merge control, this study by Cao et al. considered oversimplified cases and the developed model may not be generalized to solve real-world merge control problems.

Although these studies [5,6,7,8,9] suggest that connected and/or autonomous vehicles can improve traffic safety and increase traffic throughput at freeway ramps, none of them looked at how to optimally coordinate the movements of freeway and ramp vehicles in a complex and realistic setting. In this paper, a nonlinear optimization model is developed for this purpose. This model takes the second-by-second accelerations of all vehicles as the decision variables and tries to maximize the total speed of all vehicles over the next short time period. It also ensures that when a vehicle arrives at the merging point, the distance headways between it and adjacent vehicles are greater than a minimum value to guarantee safety. In addition, a simulation platform is developed based on VISSIM, MATLAB, and the VISSIM Car2X module to quantify the benefits of this optimal ramp control strategy. The optimization model is detailed in Section 2. Section 3 describes the simulation platform. The proposed model and simulation platform are validated in Section 4 using several case studies. Section 4 also describes the plan to evaluate the proposed optimal control strategy using simulation. The simulation results are presented and discussed in Section 5. Section 6 provides conclusions and recommendations for future research.

## 2. MODEL FORMULATION

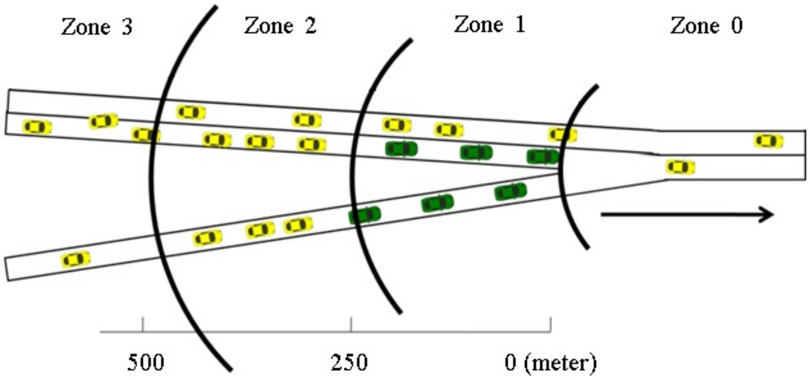


**FIGURE 1 Freeway on-ramp considered in this study.**

Figure 1 shows a typical freeway on-ramp, based upon which the proposed control model is formulated. The freeway segment under investigation is about 1,000 meters long. The location where the ramp and the freeway connect is called the merging point. A merging zone is defined as a segment of the right-most lane of the freeway that is within 250 meters downstream of the merging point. Under the connected vehicle environment, freeway vehicles will be informed of the traffic conditions in the merging zone and on the ramp. Based on such information, freeway vehicles may slow down, accelerate, or shift to the left lane to allow vehicles from the ramp to join the freeway. They may also choose to do nothing. To model such behaviors, four reaction zones, Zones 0 through 3, are considered in this study. As shown in Figure 1, Zones 1~3 are [0, 250), [250, 500), and [500, ∞) meters upstream of the merging point, respectively. Zone 0 is [0, ∞) meters downstream of the merging point.

This study assumes that all lane changes are completed in Zone 3. Upon entering Zone 2, vehicles switch to the autonomous driving mode until they enter Zone 0. In Zones 2 and 1, freeway vehicles are not allowed to change lanes. Zone 2 is for both freeway and ramp vehicles to adjust their longitudinal trajectories based on the optimal control model described below. Following the optimized trajectories, these vehicles can safely pass the merging point without any conflicts. Upon entering Zone 1, all vehicles should travel at a constant speed. Once these vehicles leave Zone 1, human drivers can take over the vehicle control. The proposed optimal ramp control model is based on a strict assumption that all vehicles are connected via Dedicated Short-Range Communications (DSRC). Once freeway and ramp vehicles are in Zone 2, they will turn the control over to a central traffic controller and strictly execute the instructions received from the central controller.

The optimal control strategy is formulated as a nonlinear optimization problem as shown in (1) through (7).

$$\text{Min}\ \left(-\sum_{i=1}^{2}\sum_{j=1}^{n_i}\sum_{k=1}^{m} v_{i,j,t_k}\right) \tag{1}$$

s.t.

$$0 \le v_{i,j,t_k} \le v_{max} \qquad \forall i,j,k \tag{2}$$

$$G_{min} \le \left|x_{i,j,t_k} - x_{i,j-1,t_k}\right| \qquad \forall i,k; j = 2,\dots,n_i \tag{3}$$

$$G_{min} \le \left|x_{1,j,m} - x_{2,p,m}\right| \qquad \forall j = 1,\dots,n_1; p = 1,\dots,n_2 \tag{4}$$

$$\left|a_{i,j,t_k} - a_{i,j,t_{k+1}}\right| \le a_{\max\_diff} \qquad \forall i,j; k = 1,\dots,m-1 \tag{5}$$

$$\frac{x_{i,j,t_{k+1}} - x_{i,j,t_k}}{t_{k+1}-t_k} = v_{i,j,t_k};\ \frac{v_{i,j,t_{k+1}} - v_{i,j,t_k}}{t_{k+1}-t_k} = a_{i,j,t_k} \quad \forall i,j; k = 1,\dots,m-1 \tag{6}$$

$$a_{min} \le a_{i,j,t_k} \le a_{max} \quad \forall i,j;k \tag{7}$$

Where $i$ = lane identifier (1-ramp and 2-freeway right lane), $j, p$ = vehicle index, $k$ = time step index, $m$ = total number of time steps ($m$=10 for this study), $n_i$ = total number of vehicles in Zone 2 of lane $i$, $t_k$ = the $k^{th}$ time step, $a_{i,j,t_k}$ = acceleration of vehicle $j$ in lane $i$ at time step $t_k$, $v_{i,j,t_k}$ = velocity of vehicle $j$ in lane $i$ at time step $t_k$, $x_{i,j,t_k}$ = distance of vehicle $j$ in lane $i$ at time step $t_k$ to the merging point, $v_{max}$ = speed limit, $G_{min}$ = minimum distance gap, $a_{min}$ = minimum acceleration rate, $a_{max}$ = maximum acceleration rate, and $a_{\max\_diff}$ = maximum acceleration rate change between two consecutive time steps.

A decision interval of 10 seconds (i.e., $m$=10) is considered. This interval is further divided into 10 1-second decision steps. At the beginning of each 1-second decision step, each vehicle needs to decide its acceleration rate, which is a decision variable of the above optimization model. By optimizing these acceleration rates, the optimal control model aims to maximize the total speed of all merging vehicles in each decision step subject to the following constraints:

- Constraints (2) ensure that each vehicle maintains a nonnegative speed ($v_{i,j,t_k}$) that is no greater than the speed limit;
- Constraints (3) require that the distance between two consecutive vehicles in the same lane must be greater than a minimum value $G_{min}$;

- Constraints (4) make sure that any pair of freeway and ramp vehicles maintains a safe distance at the end of the decision interval (i.e., when $k = 10$). This is achieved by projecting ramp vehicles onto the freeway using the merging point as the reference;
- Constraints (5) limit the acceleration rate changes of each vehicle between two consecutive time steps to prevent aggressive driving behaviors;
- Constraints (6) describe the relationships among speed, acceleration, and distance. Acceleration is the derivative of velocity with respect to time, and velocity is the derivative of distance traveled to time; and
- Constraints (7) ensure that each vehicle maintains an acceleration rate that is no larger that $a_{max}$ and no less that $a_{min}$ at each time step.

To further prevent aggressive driving behaviors from happening, the original objective function (1) is modified by adding a second term as shown in (8), where $SD_{i,j}$ is the standard deviation of accelerations for vehicle $j$ in lane $i$. This new term is identical to the notion of Acceleration Noise which has been used previously in traffic flow control [10]. This new objective function has been used to carry out all the case studies and simulations in this research.

$$\text{Min}\left(-\sum_{i=1}^{2}\sum_{j=1}^{n_i}\sum_{k=1}^{m} v_{i,j,t_k} + \sum_{i=1}^{2}\sum_{j=1}^{n_i} SD_{i,j}\right) \tag{8}$$

## 3. DEVELOPMENT OF MODELING FRAMEWORK

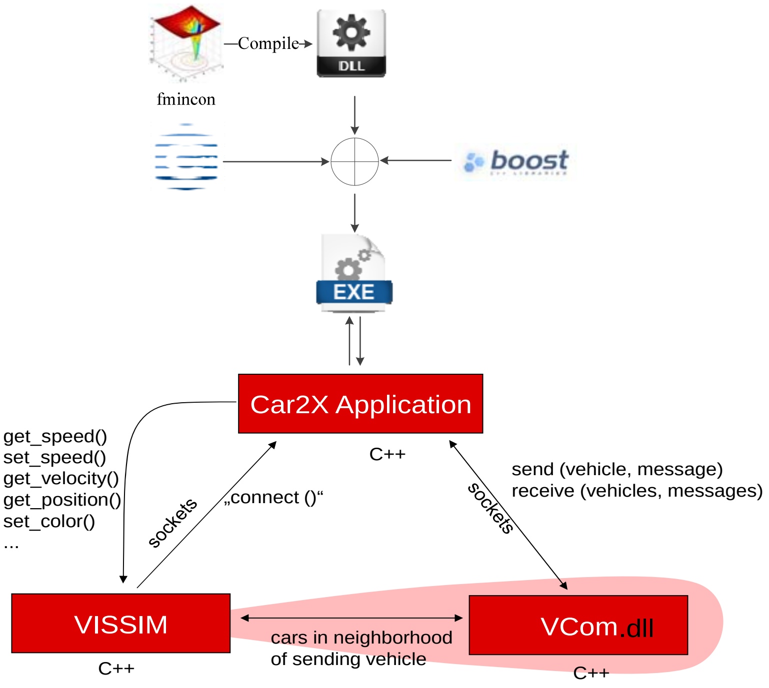
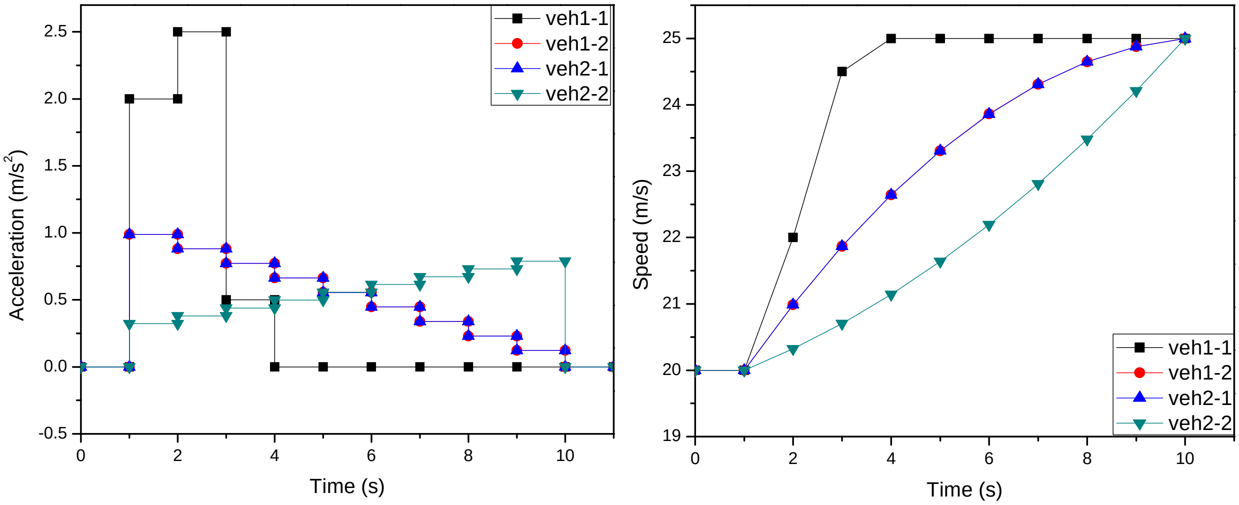


**FIGURE 2 Integrated platform architecture**

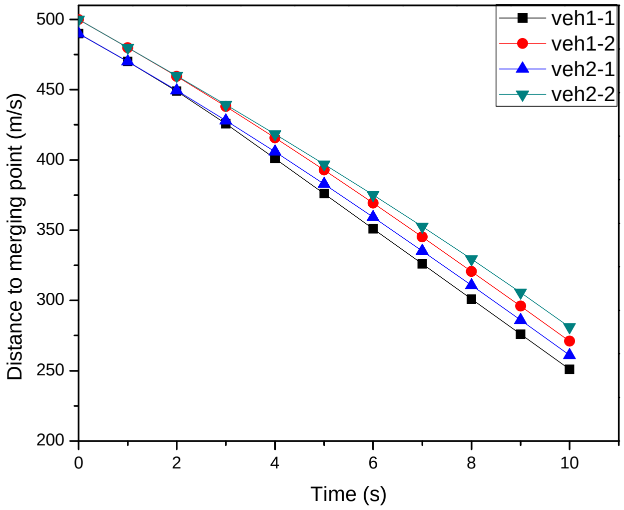
To evaluate to what extent the optimal control model can improve traffic operations at freeway on-ramps, an integrated modeling platform is developed. First, a microscopic traffic simulator, VISSIM, is integrated into the platform to simulate the merging process at freeway on-ramps.

With the VISSIM simulator and the Car2X module included in it, the accelerations, speeds and positions of all vehicles in Zone 2 can be captured precisely. This information is fed into an optimization module coded in MATLAB. The optimization module takes all the inputs and finds the optimal control strategies (i.e., accelerations) for each vehicle. These optimal strategies are sent back to the VISSIM simulator for vehicle control. To facilitate the data exchange between MATLAB and VISSIM, a C++ application is developed. The optimization module written in MATLAB is encapsulated into a dynamic-link library and called by the C++ application. This C++ application is then compiled as an executable file to override the default driver behavior model in VISSIM. Figure 2 illustrates the architecture of the modeling platform.

## 4. MODEL VALIDATION AND EXPERIMENTAL DESIGN



(a) Acceleration vs. Time (b) Speed vs. Time



(c) Distance vs. Time

**FIGURE 3 Optimization results for case study I.**

### 4.1. Model Validation

To demonstrate how the optimization-based control algorithm works and to verify the effectiveness of the proposed model, two case studies are conducted. In both studies, the following parameters are used: $v_{max}$ = 25 meter/second (about 60 mph), $a_{max}$ = 5 m/s$^2$, $a_{min}$ = -5 m/s$^2$, $a_{\max\_diff}$ = 2 m/s$^2$, and $G_{min}$ = 10 m. Since vehicles are not allowed to change lanes in Zones 2 and 1, only one lane is considered for the freeway in this study.

### 4.1.1. Case Study I - Four Vehicles

In this case study, two freeway vehicles and two ramp vehicles are considered. The initial accelerations and speeds of all vehicles are assumed to be 0 m/s$^2$ and 20 m/s, respectively. The initial vehicle states are summarized below. Clearly, if all vehicles maintain their initial speeds, the freeway and ramp vehicles will run into each other at the merging point.

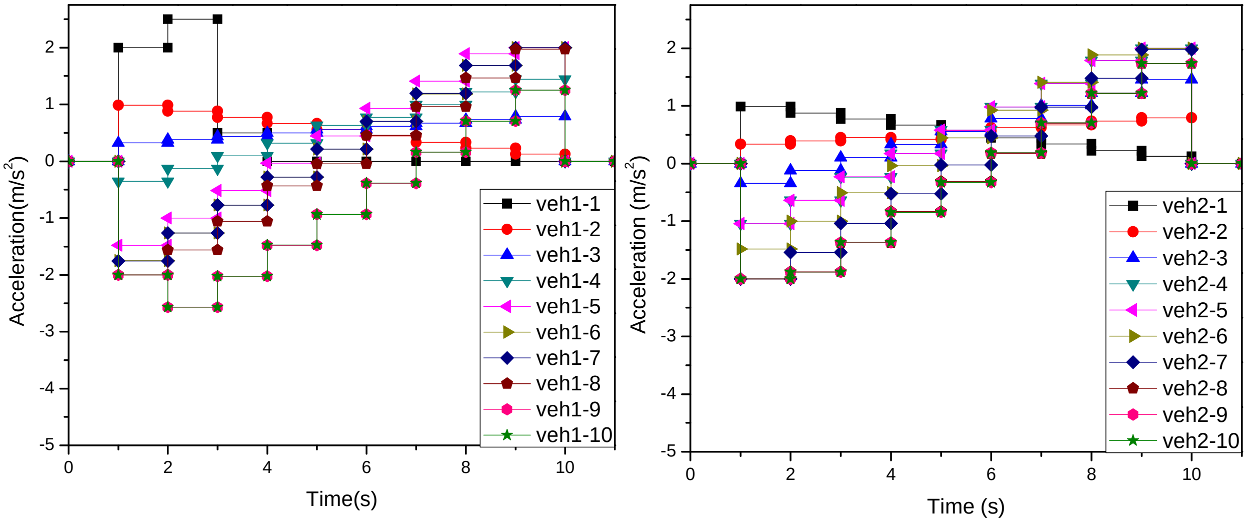
$$\begin{aligned} x_{1,j,0} &= [490 \quad 500], & x_{2,j,0} &= [490 \quad 500], \\ v_{1,j,0} &= [20 \quad 20], & v_{2,j,0} &= [20 \quad 20], \\ a_{1,j,0} &= [0 \quad 0], & a_{2,j,0} &= [0 \quad 0] \end{aligned}$$

The modeling results for this case study are summarized in FIGURE 3. Veh1-1 and veh1-2 stand for the first and second vehicles on the freeway and veh2-1 and veh2-2 denote the two vehicles on the ramp. Figure 3(a) clearly shows that the constraints on accelerations are satisfied. Since the initial speeds are all less than the speed limit, the vehicle accelerations are all positive. These vehicles adopt different acceleration patterns in order to maximize their speeds and maintain sufficiently large distance headways at the time they arrive at the merging point. As shown in Figure 3(b), none of the four vehicles exceed the 25 m/s speed limit and their speeds all reach 25 m/s at the end of the 10-second decision interval. The time-space diagram in Figure 3(c) shows the trajectories of the four vehicles. This is done by projecting the four vehicles onto a single lane and using the merging point as the reference point for calculating the distance. At the beginning, the distance headway between veh1-1 and veh2-1 is 0. The same thing is true for veh1-2 and veh2-2. By executing the optimal acceleration instructions produced by the model, the four vehicles can pass the merging point safely with a minimum headway of 10 meters.

### 4.1.2. Case Study II - Twenty Vehicles

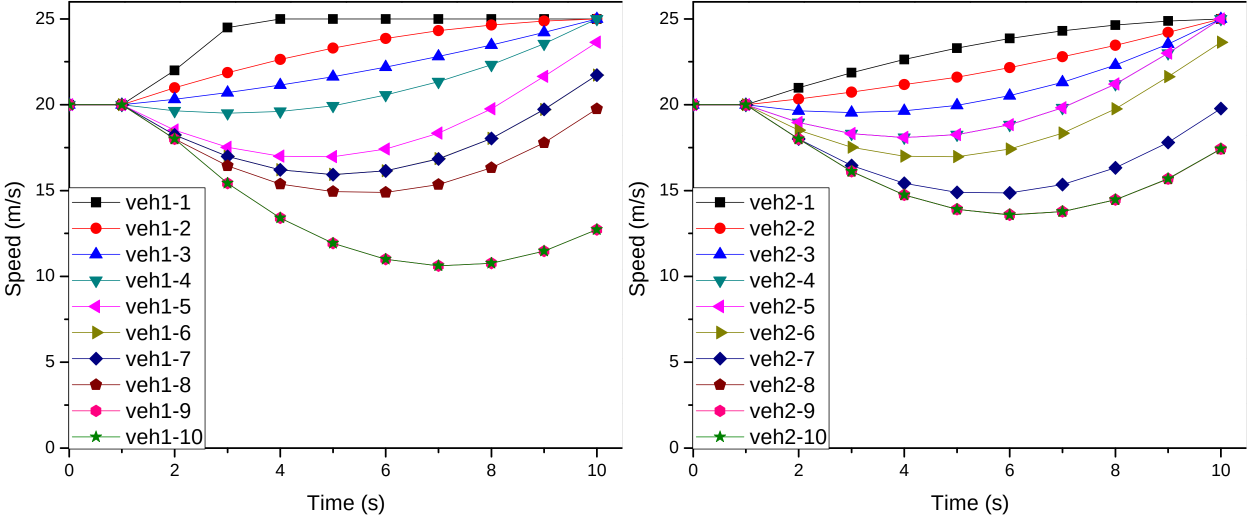
Case study II is used to validate the optimal control model's performance under heavy traffic conditions. It considers ten freeway vehicles and ten vehicles on the ramp in Zone 2. The initial states of all vehicles are:

$$\begin{aligned} \mathrm{x}_{1,\mathrm{j},0} &= [500\ 490\ 480\ 470\ 460\ 450\ 440\ 430\ 420\ 410] \\ \mathrm{x}_{2,\mathrm{j},0} &= [500\ 490\ 480\ 470\ 460\ 450\ 440\ 430\ 420\ 410] \\ \mathrm{v}_{1,\mathrm{j},0} &= [20\ 20\ 20\ 20\ 20\ 20\ 20\ 20\ 20\ 20] \\ \mathrm{v}_{2,\mathrm{j},0} &= [20\ 20\ 20\ 20\ 20\ 20\ 20\ 20\ 20\ 20] \\ \mathrm{a}_{1,\mathrm{j},0} &= [0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0] \\ \mathrm{a}_{2,\mathrm{j},0} &= [0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0] \end{aligned}$$



(a) Acceleration vs. Time
for vehicles on highway

(b) Acceleration vs. Time
for vehicles on ramp



(c) Speed vs. Time
for vehicles on highway

(d) Speed vs. Time
for vehicles on ramp

**FIGURE 4 Optimized speed and acceleration results for case study II.**

The speed and acceleration profiles of the twenty vehicles are presented in Figure 4. Because of the relatively large number of vehicles, the acceleration profiles are mixed together. Compared to those for case study I, the acceleration profiles here are also more difficult to interpret due to the complicated interference among the different vehicles. Nevertheless, the results indicate that constraints (5) and (7) are satisfied. Figures 4(c) and 4(d) show that some vehicles may not be able to reach the speed limit (25 m/s) when they pass the merging point due to congestion. These vehicles have to slow down in order to create safe gaps for each other. Figure 5 below shows the trajectories of the twenty vehicles. The pattern shown in Figure 5 is very similar to that in Figure 3. If all vehicles are projected onto a virtual lane, at the end of the 10-second interval, one will see a platoon of approximately evenly-spaced vehicles.

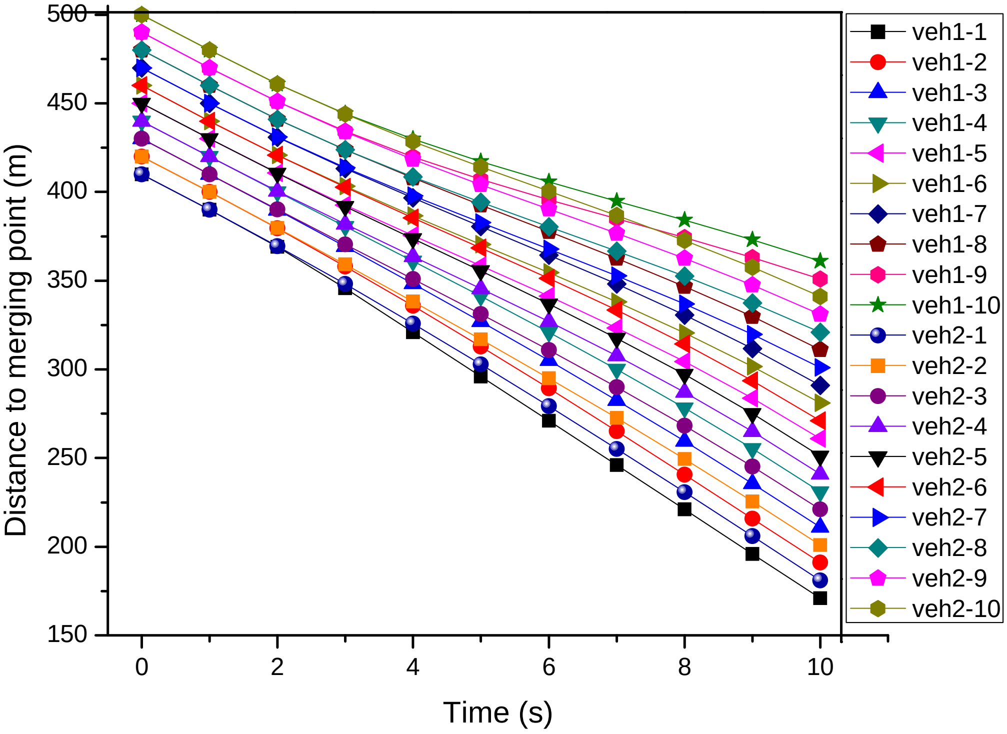
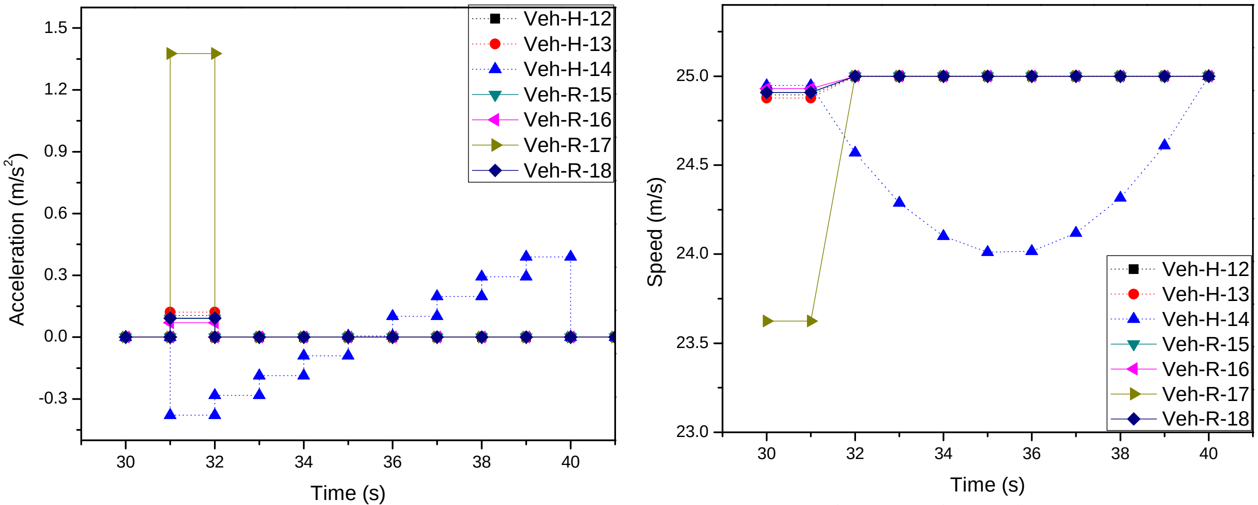


**FIGURE 5 Optimized time-distance diagram for case study II.**

## 4.2. Simulation Framework Validation

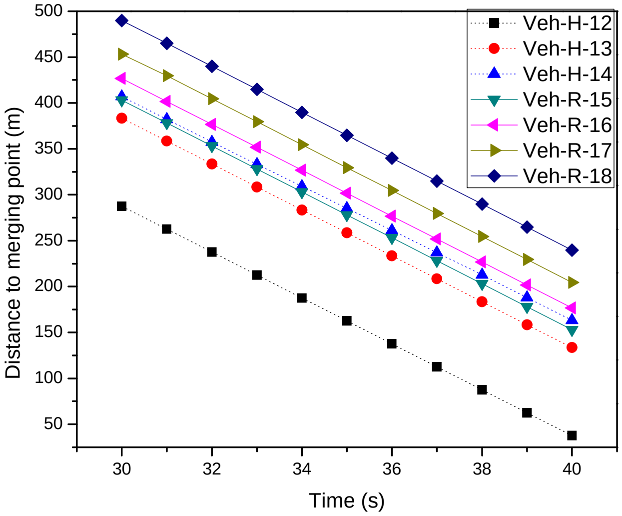
This validation study is to examine the integration of VISSIM, MATLAB, and Car2X. It is done by comparing the optimized control instructions generated by MATLAB with the VISSIM control results. For this validation, the freeway and ramp vehicle inputs are set to 1,000 veh/h and 500 veh/h, respectively. A random seed of 19 is used in VISSIM to run the simulation. The simulated vehicle trajectories between 30s and 40s from the beginning of the simulation are recorded and compared with those calculated by the optimal control model coded in MATLAB.

At 30s, there are 7 vehicles in Zone 2. Veh-H-12, Veh-H-13, and Veh-H-14 are on the freeway and Veh-R-15, Veh-R-16, Veh-R-17, and Veh-R-18 are on the ramp. Their distances from the merging point, their speeds and accelerations are plotted in Figure 6. Between 30s and 40s, these vehicles meet all the speed and acceleration constraints. Table 1 shows the distances of each vehicle to the merging point at different time steps. D1 in Table 1 is the minimum distance between any two vehicles in the same lane. D2 is the minimum distance between any two vehicles from different lanes in Zone 2. The data in Table 1 shows how vehicles adjust their speeds to create safe gaps at the merging point. At 30s, D2 is 4.09 m, which is between Veh-H-14 and Veh-R-15. Therefore, at least one of these two vehicles should either accelerate or decelerate. At the end of the optimization, D2 has been increased to 10.02 m, which is larger than the required minimum safe distance of 10 m.



(a) Acceleration vs. Time

(b) Speed vs. Time



(c) Distance vs. Time

**FIGURE 6 Data collected from VISSIM simulation.**

**TABLE 1 Distance to merging point for vehicles**

| **Time (s)** | **Distance to merging point (meter)** | | | | | | | D1 | D2 |
|---|---|---|---|---|---|---|---|---|---|
| | **Veh-H-12** | **Veh-H-13** | **Veh-H-14** | **Veh-R-15** | **Veh-R-16** | **Veh-R-17** | **Veh-R-18** | | |
| **30** | 287.46 | 383.36 | 407.10 | 403.01 | 426.66 | 453.20 | 489.77 | 23.75 | 4.09 |
| **31** | 262.57 | 358.48 | 382.15 | 378.10 | 401.73 | 429.57 | 464.86 | 23.68 | 4.05 |
| **32** | 237.57 | 333.48 | 357.58 | 353.10 | 376.73 | 404.57 | 439.86 | 24.11 | 4.48 |
| **33** | 212.57 | 308.48 | 333.30 | 328.10 | 351.73 | 379.57 | 414.86 | 24.82 | 5.20 |
| **34** | 187.57 | 283.48 | 309.19 | 303.10 | 326.73 | 354.57 | 389.86 | 25.72 | 6.09 |
| **35** | 162.57 | 258.48 | 285.18 | 278.10 | 301.73 | 329.57 | 364.86 | 26.70 | 7.08 |
| **36** | 137.57 | 233.48 | 261.17 | 253.10 | 276.73 | 304.57 | 339.86 | 27.69 | 8.07 |
| **37** | 112.57 | 208.48 | 237.05 | 228.10 | 251.73 | 279.57 | 314.86 | 28.57 | 8.95 |
| **38** | 87.57 | 183.48 | 212.73 | 203.10 | 226.73 | 254.57 | 289.86 | 29.25 | 9.63 |
| **39** | 62.57 | 158.48 | 188.12 | 178.10 | 201.73 | 229.57 | 264.86 | 29.64 | 10.02 |
| **40** | 37.57 | 133.48 | 163.12 | 153.10 | 176.73 | 204.57 | 239.86 | 29.64 | 10.02 |

Table 2 shows the accelerations recorded during the VISSIM simulation. The acceleration value in each time step was recorded at the end of the step (i.e., the acceleration of 0.1054 for Veh-H-12 at 32s means the acceleration from 31s to 32s is 0.1054). Table 3 shows the accelerations suggested by the optimal control model coded in MATLAB. The suggested acceleration is given at the beginning of each time step (i.e., the acceleration of 0.105387 for Veh-H-12 at 31s is for the time step between 31s and 32s). Comparing the values in Tables 2 and 3 indicates that VISSIM strictly follows the accelerations obtained by the optimal control model. The maximum difference between the optimized and actually executed accelerations is 0.0001 m/s$^2$ at 32s for Veh-H-14, which is negligible.

**TABLE 2 Recorded accelerations during VISSIM simulation**

| **Time (s)** | **Highway** (m/s$^2$) | | | **Ramp** (m/s$^2$) | | | |
|---|---|---|---|---|---|---|---|
| | **Veh-H-12** | **Veh-H-13** | **Veh-H-14** | **Veh-R-15** | **Veh-R-16** | **Veh-R-17** | **Veh-R-18** |
| **30** | | | | | | | |
| **31** | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **32** | **0.1054** | **0.1223** | **-0.3782** | **0.0914** | **0.0701** | **1.3757** | **0.0917** |
| **33** | 0 | 0 | **-0.2823** | 0 | 0 | 0 | 0 |
| **34** | 0 | 0 | **-0.1862** | 0 | 0 | 0 | 0 |
| **35** | 0 | 0 | **-0.0903** | 0 | 0 | 0 | 0 |
| **36** | 0 | 0 | **0.0057** | 0 | 0 | 0 | 0 |
| **37** | 0 | 0 | **0.1018** | 0 | 0 | 0 | 0 |
| **38** | 0 | 0 | **0.1977** | 0 | 0 | 0 | 0 |
| **39** | 0 | 0 | **0.2937** | 0 | 0 | 0 | 0 |
| **40** | 0 | 0 | **0.3897** | 0 | 0 | 0 | 0 |

**TABLE 3 Suggested accelerations calculated in MATLAB**

| **Time (s)** | **Highway** (m/s$^2$) | | | **Ramp** (m/s$^2$) | | | |
|---|---|---|---|---|---|---|---|
| | **Veh-H-12** | **Veh-H-13** | **Veh-H-14** | **Veh-R-15** | **Veh-R-16** | **Veh-R-17** | **Veh-R-18** |
| **30** | | | | | | | |
| **31** | **0.105387** | **0.122316** | **-0.37824** | **0.091373** | **0.070093** | **1.375658** | **0.091721** |
| **32** | -4.4E-35 | 0 | **-0.28224** | -1.6E-18 | 0 | -2.9E-17 | 0 |
| **33** | 0 | 0 | **-0.18626** | -6E-18 | -9.9E-32 | 4.23E-18 | 2.33E-18 |
| **34** | 0 | 0 | **-0.09026** | -2.8E-18 | 9.86E-32 | 8.05E-17 | 1.15E-19 |
| **35** | -4.1E-32 | -4.1E-32 | **0.00572** | -1E-17 | -8.4E-18 | 1.04E-16 | 5.88E-18 |
| **36** | 9.86E-32 | 0 | **0.101721** | -8.5E-18 | -7.9E-18 | -8.3E-17 | 4.88E-18 |
| **37** | 0 | 0 | **0.197722** | 8.1E-19 | 8.52E-18 | 3.02E-17 | -8.2E-33 |
| **38** | -3.9E-31 | 0 | **0.293723** | -6.8E-17 | 1.02E-18 | -1.2E-17 | -5.5E-17 |
| **39** | 4.93E-32 | -3.9E-31 | **0.3897** | 6.21E-17 | -7.3E-18 | 6.32E-17 | 1.09E-16 |
| **40** | 0 | 0 | 0 | 1.37E-35 | 0 | 0 | 0 |

## 4.3. Experimental Design

The previous validation studies show that the proposed optimal control model and integrated simulation platform work under both low and heavy traffic conditions. To further demonstrate their effectiveness, in the rest of this paper, this optimal control model and platform are applied to various traffic scenarios against two other control cases. The different control cases to be evaluated and compared are summarized below.

- **Case 0**: As its name suggests, this case does not consider any communications among vehicles or any autonomous vehicles. It simply lets human drivers coordinate their merging behaviors and is introduced as a benchmark (i.e., do nothing). All vehicles follow the default driver behavior models included in VISSIM.
- **Case 1**: If the speed of any vehicles in Zone 0 is less than 45 km/h, upstream vehicles in Zones 1 and 2 will be advised to reduce their speeds to 50km/h and 70km/h, respectively. Since the same distance headway will be considered safer under a lower traffic speed, this strategy may create additional safe gaps and allow more on-ramp traffic to merge onto the freeway.
- **Case 2**: This is the same as the proposed optimal control strategy. Trajectories of vehicles in Zone 2 will be collected every 10 seconds. The information is sent to MATLAB for optimization and the optimized accelerations for each vehicle in the next decision interval (10s long) will be sent back to the related vehicles. These vehicles will then strictly follow these optimized acceleration instructions.

For the comparison, three levels of traffic demand (low, medium, high) are considered for the freeway, which are 800 veh/h, 1,000 veh/h, and 1,200 veh/h. Similarly, the on-ramp traffic flow rate is assumed to be 300 veh/h, 500 veh/h, and 700 veh/h, respectively. In total, there are 9 different combinations of traffic demand. In all the simulations, the default Wiedemann 99 car-following model and free lane selection behavior in VISSIM are adopted. In addition, vehicles follow the same constraints as described at the beginning of Section 4.1 except for $G_{min}$ = 15 m. Each simulation run represents 3,600 seconds of ramp operations in the real world.

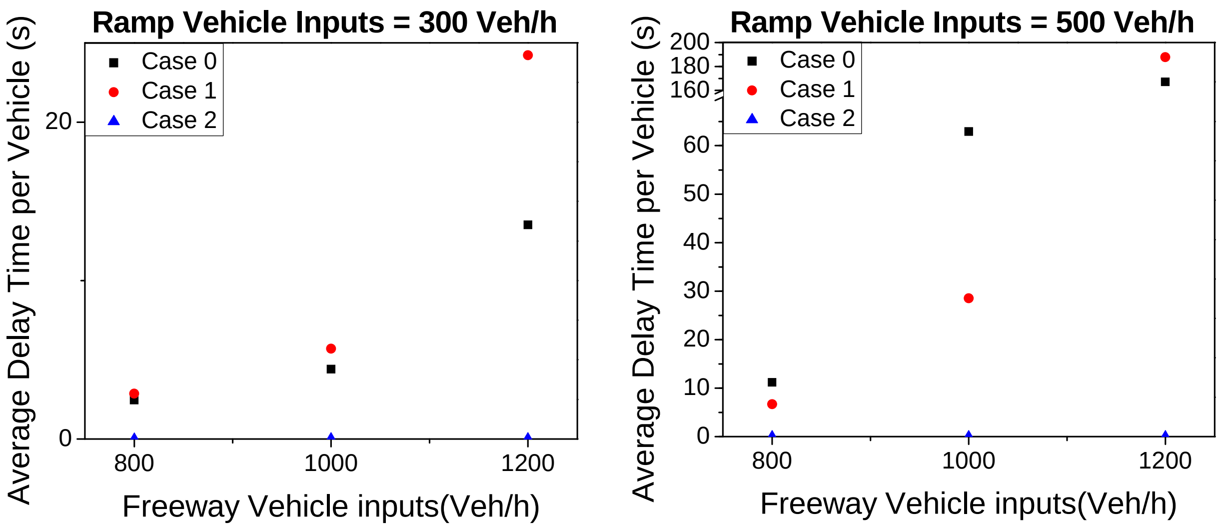
## 5. RESULT ANALYSIS AND CONCLUSION

The three cases are compared in terms of average delay time, average speed, and traffic throughput. In the following sections, the outputs for each of the three measurements of effectiveness are presented and discussed in detail.

### 5.1. Average Delay Time

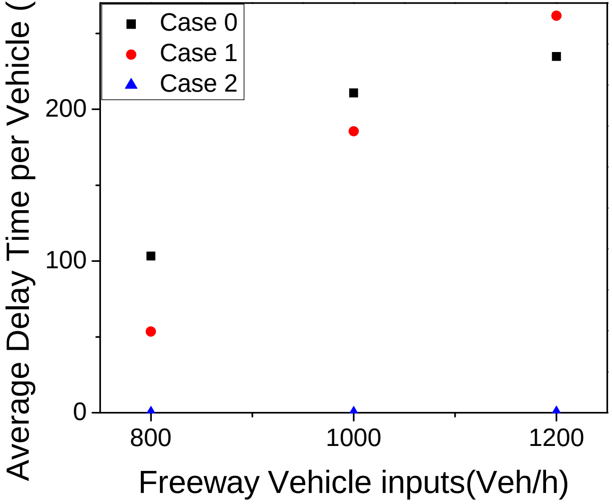
The average delay time results, grouped by the on-ramp traffic flow, are shown in Figure 7. Figure 7(a) shows the average delay time results with the on-ramp traffic flow being 300 veh/h. Figures 7(b) and 7(c) present the results for the on-ramp traffic flow being 500 veh/h and 700 veh/h, respectively.

As shown in Figure 7(a), when both the freeway and on-ramp flows are low, there is no significant difference between Cases 0 and 1. As the freeway traffic flow increases, Case 0 significantly outperforms Case 1. This suggests that reducing freeway traffic speed is unnecessary for light ramp traffic. The results in Figure 7(b) (ramp traffic = 500 veh/h) indicates that Case 1 performs significantly better than Case 0 for almost all scenarios except when the freeway traffic flow is 1,200 veh/h. This is probably because when the freeway traffic is low to medium, it is possible to create additional safe gaps for merging ramp vehicles by reducing the speeds of freeway vehicles. However, it is impossible to do so when the freeway traffic is heavy. The results in Figure 7(c) show the same trend as in Figure 7(b). For all traffic flow scenarios considered in this study, Case 2 performs the best and its delay time is almost negligible.



(a) Low on-ramp traffic

(b) Medium on-ramp traffic

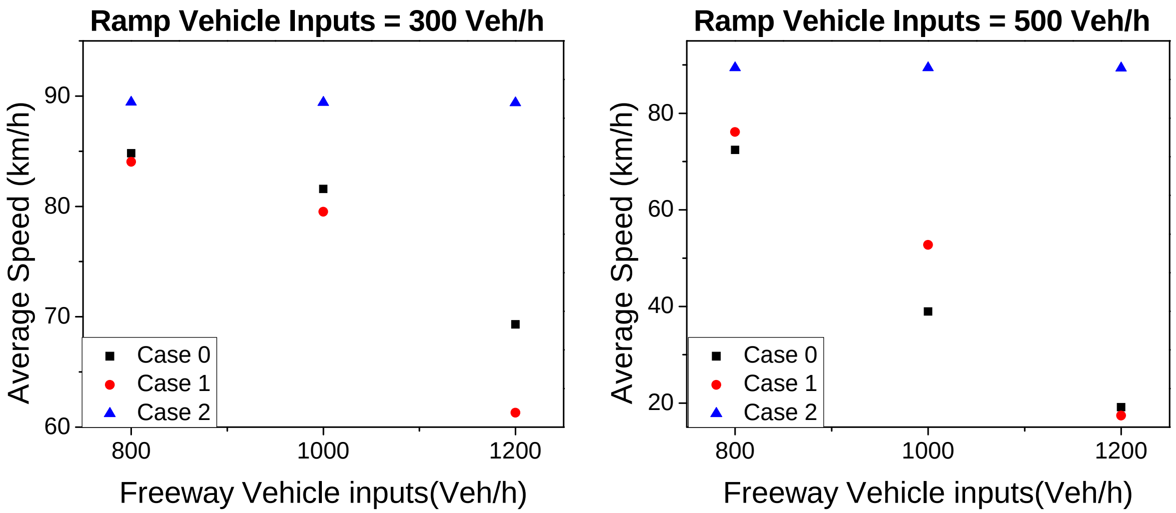


(c) High on-ramp traffic

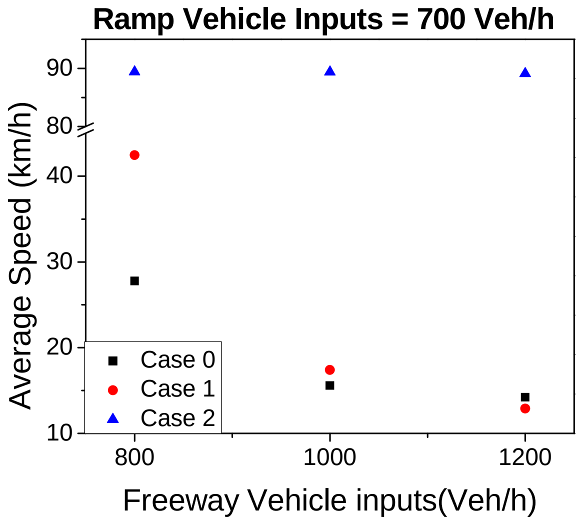
**FIGURE 7 Average delay time comparison.**

### 5.2. Average Speed

Figure 8 shows the average speed results grouped by the on-ramp traffic flow. For all traffic scenarios considered, Case 2 performs very well and its average speeds are barely affected by the varying traffic flows. On the contrary, the average speeds of both Cases 0 and 1 are significantly reduced by the heavy traffic flows of both ramp and freeway. For high ramp and low freeway flows, Case 1 significantly outperforms Case 0. In this case, reducing the speeds of freeway vehicles can help to create additional safe gaps for ramp vehicles to merge onto the freeway. The overall network average speed thus is increased. However, for low ramp (300 veh/h) or heavy freeway (1,200 veh/h) traffic flows, Case 0 consistently performs better than Case 1. This suggests that the gradual speed limit strategy should take into consideration both ramp and freeway traffic conditions.



(a) Low on-ramp traffic (b) Medium on-ramp traffic



(c) High on-ramp traffic

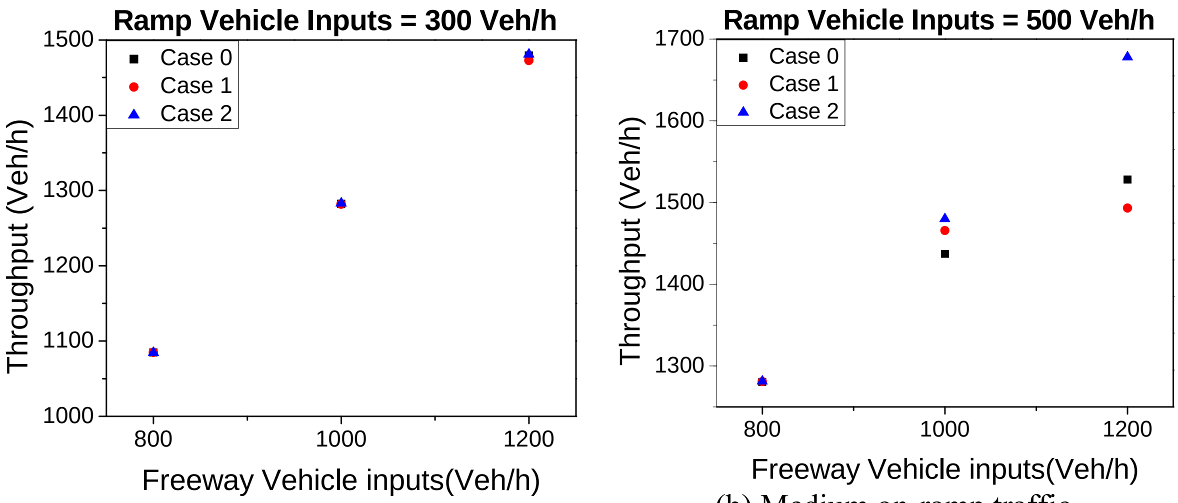
**Figure 8 Average speed comparison.**

## 5.3. Traffic Throughput

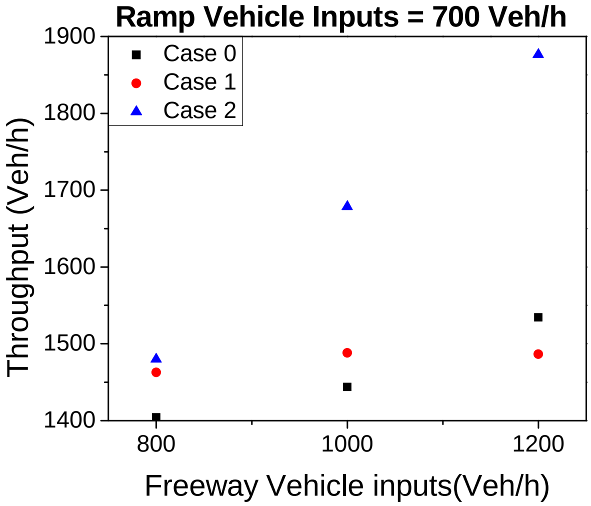
The traffic throughput results in Figure 9 are consistent with the average delay time and average speed results. When the ramp traffic flow is low (300 veh/h), there is no major difference among the three cases. As the ramp or freeway traffic flow increases, the differences among the three cases become more significant. In general, Case 2 performs the best and it allows all vehicles to clear the network for all scenarios. Case 1 performs better than Case 0 when the ramp traffic is heavy and the freeway traffic flow is low. Again, Case 0 outperforms Case 1 when the freeway traffic flow is high and the ramp flow is low.

## 6. CONCLUSION

This paper proposes and evaluates an optimization-based ramp control strategy assuming all vehicles are connected and controlled automatically. A simulation platform is developed integrating VISSIM, MATLAB, and the Car2X module in VISSIM. The proposed optimal ramp control strategy is formulated as a nonlinear optimization problem and solved using the MATLAB optimization toolbox. This optimization model divides the decision interval into 1-second time steps. Based on the initial speeds, accelerations, and locations of all vehicles, the control algorithm takes the second-by-second accelerations of each vehicle as the decision variable and optimizes them. The optimized accelerations are then used to control these vehicles during the next decision interval.



(a) Low on-ramp traffic (b) Medium on-ramp traffic



(c) High on-ramp traffic

**Figure 9 Throughput comparison.**

Three case studies are conducted to validate the effectiveness of the developed optimal control model and the simulation platform. The proposed optimal control algorithm (Case 2) is further compared with a do-nothing strategy (Case 0) and a gradual speed limit strategy (Case 1) for controlling a typical freeway on-ramp. Various levels of freeway and on-ramp traffic flows are considered, which results in nine test scenarios. These three ramp control strategies are compared in terms of average delay time, average speed, and traffic throughput. When either the freeway or the on-ramp traffic flow is low, there is no significant difference among the three control strategies in terms of throughput. This is likely because ramp vehicles can all find a safe gap to join the freeway without causing long standing queues. For the remaining scenarios considered, the optimal control strategy substantially outperforms the other two strategies. When the freeway traffic is heavy and the on-ramp traffic is light, the gradual speed limit strategy performs even worse than not considering any control. This gradual speed limit strategy works when the freeway traffic flow is low and the on-ramp has a medium to heavy traffic.

The results demonstrate the potential effectiveness of the proposed optimization-based ramp control strategy. However, it is based on a strict assumption that all vehicles are connected and controlled automatically. In future studies, it would be interesting to consider how to optimally control a mixture of autonomous vehicles and vehicles controlled by human drivers. Also, multilane freeways can be considered instead of a single-lane freeway. In this case, lane changing decisions can be included as decision variables in addition to the acceleration rates.

## 7. ACKNOWLEDGMENT

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