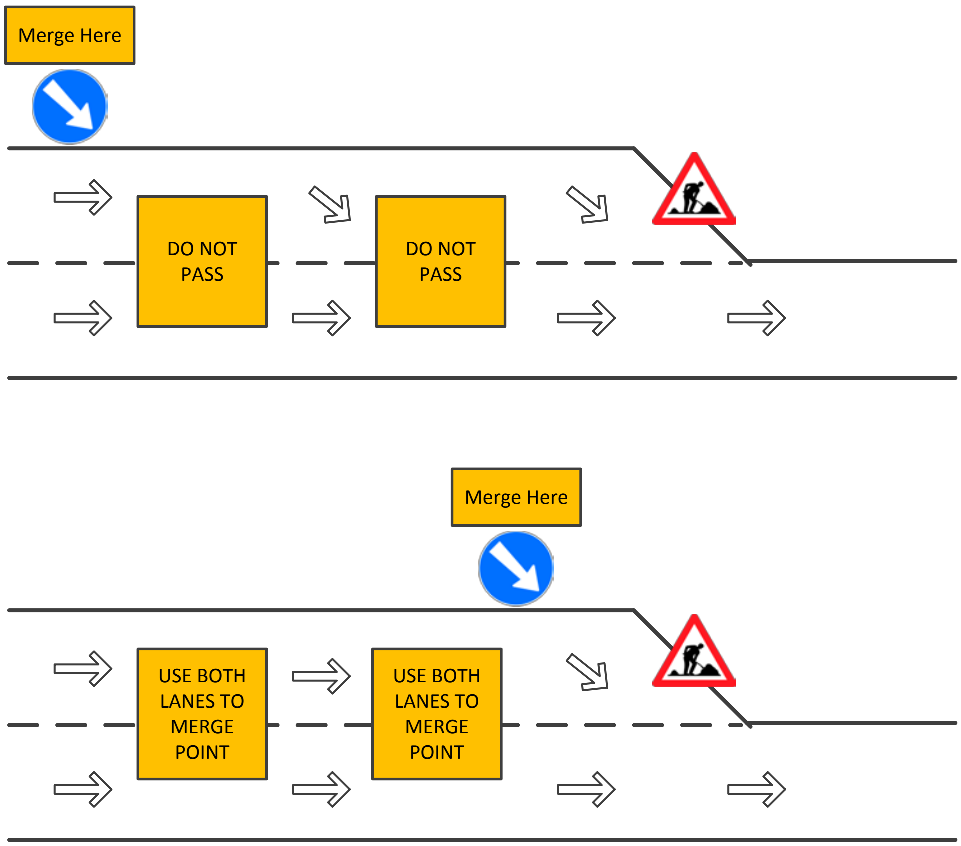

A Simulation Study for the Static Early Merge and Late Merge Controls at Freeway Work Zones

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Abstract

The merge control has been proposed as a way to maximize the utilization of road capacity at the work zone area. Two of the most widely used merge control schemes are the static Early Merge (EM) control and the static Late Merge (LM) control. Although many papers adopted field measurements and/or microscopic traffic simulations to explore the performance of these two control schemes, they seldom cross compared them under the same work zone settings, and some of them even derived conflicting results.

To extensively investigate and cross compare the traffic performance of the EM and LM controls, we conducted a simulation study using the microscopic traffic simulator VISSIM for a 2-to-1 lane closure work zone. In addition, the sensitivity analysis was adopted to determine the influential VISSIM parameters with respect to the work zone throughput.

It is found that the parameters *CC1* (i.e., headway time) and *CC2* (i.e., longitudinal following threshold in the car-following process) have significant impacts on the simulated work zone throughput. In addition, adjusting *CC1* can make the throughput drop faster in the EM scenarios than in the LM scenarios. The simulations also show that when *CC1* is low, the work zone capacity under the EM control is higher and the queue is shorter. On the contrary, when *CC1* is high, the work zone with LM control has a higher capacity and shorter queue. As the parameter *CC1* is critical to the simulation results, it should be carefully calibrated and validated in the VISSIM-based merge control simulations.

Based on the simulation results, we recommended that it is more appropriate to implement the EM control when the drivers are aggressive and the safety distance is relatively short (i.e., *CC1* is low); when the drivers are cautious and the safety distance is long (i.e., *CC1* is high), it is better to adopt the LM control in the work zone area.

Keywords

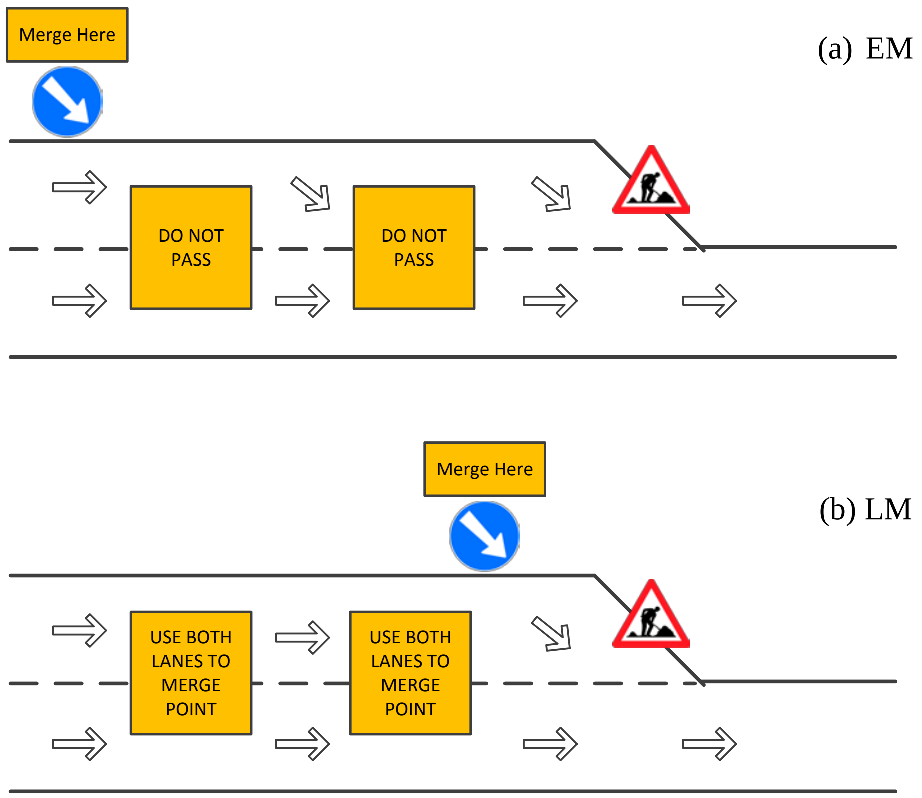
Work Zone, Static Merge Control, Microscopic Traffic Simulation, Capacity, Sensitivity Analysis

1. Introduction

The work zone is a section of road that is used to provide space for road construction or maintenance project. There is typically one or several lanes been closed in the work zone area, therefore the capacity of the road is reduced. As a result, the drivers must make lane changing and merging maneuvers upstream the lane closure in order to pass the work zone. When the traffic demand is high, these maneuvers may significantly increase the potential for traffic conflicts and accidents, and further reducing the capacity of the road. Reduction of road capacity can lead not only to the reduction of traffic mobility (i.e., increased delays, decreased throughputs), but also bring environmental problems such as higher pollution and fuel consumption.

To overcome these critical work zone issues, transportation practitioners have proposed several control schemes to maximize the utilization of road capacity at the work zone area. Two of the most widely used control schemes are the static Early Merge (EM) control and the static Late Merge (LM) control.

Figure 1 Illustration of the static EM and LM controls for a 2-to-1 lane closure work zone



The static EM control (Figure 1a) aims at encouraging drivers to merge as early as possible before they reach the mandatory merging point. The control signs providing the information about the lane drop are placed significantly upstream of the lane drop itself. This control scheme reduces the potential conflicts or frictions among the drivers merging at the last minute. As a result it might reduce the accident rates close to the merge area and guarantee the through flow.

The static LM control (Figure 1b) is just the opposite scheme of the early merge. It advocates that drivers should stay on their lane and merge as late as they can. With this strategy the control signs are still placed upstream, but they advise drivers to use all the lanes until the mandatory merging point. The idea is to fully utilize the capacity of the lanes as much as possible. This can shorten the queue along the road and reduce the possibility of blocking exits upstream of the work zone.

Many field studies can be found for evaluating the performance of the static EM and LM control schemes, as well as the dynamic forms of each scheme that can change the merge location according to the real traffic status (e.g., Pesti et al., 1999; Beacher et al., 2004; Radwan et al., 2009). However, as the field studies are often conducted at a selected time period and location, it is hard to test the control schemes under multiple traffic conditions (e.g., different demands, truck percentages, etc.). In addition, some studies have reported that the EM or LM control may confuse the drivers confused as they were not familiar with the control system when it was implemented at study sites (e.g., McCoy and Pesti, 2001; Tarko and Venugopal, 2001; Datta et al., 2004). Therefore, the data derived from these studies might not represent the true characteristics of the control system, and hence the conclusions might not be valid and convincing. Furthermore, due to the limitation of time and investment for installing the equipment, there is usually only one control scheme implemented at one specific work zone area, and it is usually hard to make a comparison of the EM and LM controls under exactly the same traffic condition in the field study.

As an alternative to the field studies, traffic simulation has grown into a major resource for the transportation researchers and practitioners in the recent years. The use of commercial traffic simulators (i.e., software) has become widespread, and these programs have indeed become necessary tools for planning and designing transportation networks. In addition, as the simulators are computer programs, they are not restricted to the observation time, location or any other field conditions; and different control schemes can be easily modeled in the simulation. Through adopting the same random seed and relevant parameters, same traffic conditions can be created and repeated in the traffic simulation at any time.

Several papers can be found that used microscopic traffic simulators, either self-developed models or commercial software, to evaluate the performance of different merge control schemes (e.g., Mousa et al., 1990; McCoy et al., 1999; Beacher et al., 2005; Chatterjee et al., 2009; Yang et al., 2009; Harb et al., 2012). Nevertheless, they seldom cross compare the EM and LM control schemes under the same work zone settings. In addition, we have found that some simulation studies even gave contradictory conclusions when comparing these two control schemes, although they adopted the same simulation model (for details see Section 2.1). Therefore, a thorough evaluation study that compares the performance of both EM and LM controls will be meaningful, and it will aid in determining when and which, if ever, merge control scheme should be considered for implementation in the work zone.

This paper describes the results of our preliminary attempts to evaluate the EM and LM with the aid of microscopic traffic simulations. The scope includes the computer simulations of the static EM and LM controls in a two-to-one lane closure scenario, and is limited to an examination of the traffic performance (e.g., capacity, queue length) at the work zone area. Safety issues are not discussed explicitly in this study.

The objectives of this study are listed as follows:

- Extensively understand the EM and LM controls as well as their benefits through traffic simulations
- Identify the simulation parameters that influence the performance of the EM and LM control schemes
- Through the knowledge gained from simulations, provide preliminary suggestions as to the most appropriate conditions under which the EM or LM should be considered

The paper is organized as follows: Section 2 briefly reviews the previous EM and LM simulation studies and the microscopic traffic simulation used here; Section 3 introduces the approach used for the experiment design; Section 4 presents the results derived from simulations; and Section 5 gives our conclusions and some recommendations for implementing the merge control.

2. Literature Review

2.1 Previous work zone EM and LM simulation studies

Several research papers were found that discussed the performance of the EM and/or LM control via traffic simulations. Mousa et al. (1990) presented a methodology for optimizing the traffic performance based on a self-developed simulation model in FORTRAN. This model was used to investigate the optimum merging strategy for the traffic at a 3-to-2 lane closure work zone area. Their simulation results showed that the optimum merging strategy that yielded the lowest travel time did not involve many early merges. On the contrary, along with the growth of the flow rate, the LM was preferred in terms of minimizing the travel time.

McCoy et al. (1999) employed the microscopic freeway simulation model WZSIM to simulate the static EM and LM control schemes in a 2-to-1 lane closure scenario. According to their simulations, compared to the no-control scenario, the earlier the drivers were informed about the lane closure, the less delay they would experience, and the work zone throughput was consequently higher. Their explanation for this phenomenon was when the drivers started to merge early, they had more opportunities to merge into the open lane and were less likely to be delayed. As a result, the speed and density in the open lane was higher, and so was the throughput. They further compared the LM and no-control scenario, and found that LM only outperformed the no-control when the traffic demand was high. This was due to "*the result of more uniform flow provided by the alternating merging pattern between the two lanes*" at high traffic demand. However, in their simulation study a cross comparison between static EM and LM was not included.

The commercial simulator VISSIM (PTV, 2012) was adopted in the research by Beacher et al. (2005) to compare the performance of LM with Traditional Traffic Control (TTC, basically it belongs to EM) under different traffic conditions (i.e., traffic demands, lane closure configurations, percentages of heavy vehicles, desired free-flow speed). The simulation results showed that LM outperformed TTC for 3-to-1 lane closure, while for 2-to-1 and 3-to-2 configurations the improvement was not statistically significant. However, when the percentage of trucks reached a certain value (e.g., 20%) and there was congestion at the work zone, LM yielded significantly higher throughputs than TTC. One possible reason was given in the paper: the trucks usually had lower acceleration rate than cars, and this characteristic could cause large gaps to open in front of the queued trucks. In the TTC drivers were informed to move out of the closed lane as soon as possible, and the overtaking was not allowed in the open lane, therefore these gaps could not be filled by other vehicles so that it wasted the road capacity. In contrast, with the LM control vehicles could travel on all lanes till the merge point, which allowed better use of the road capacity.

Chatterjee et al. (2009) investigated the relationship between VISSIM driving behavior parameters and the work zone capacity values in a typical EM system. The tests were done for the 2-to-1 and 3-to-2 lane closure scenarios, and they distinguished that the VISSIM parameters *CC1*, *CC2* and *SDRF* (for details about these parameters see the review in Section 2.2) were the most influential parameters with respect to the work zone throughput. They used the Exhaustive Search (ES) method to generate a sufficient large sample for these three parameters. As a result different capacity values that ranged from 1,200 vphpl to 2,100 vphpl could be achieved in both 2-to-1 and 3-to-2 lane closure configurations.

VISSIM was used by Yang et al. (2009) andHarb et al. (2012) for the simulation of 2-to-1 lane closure work zone configuration as well. Both studies claimed that the VISSIM model they used was calibrated with the data from field measurement, however their simulations presented different results in terms of the performance of the EM and LM. In (Yang et al. 2009), the simulation results showed that when the traffic demand was less than 750 vphpl, EM outperformed LM with respect to higher throughput; when the demand was over 750 vphpl, EM performed worse because at the high demand, "*vehicles will begin to experience the difficulty in changing lanes and consequently cause traffic disturbances … EM under such traffic conditions may result in numerous merging points and yield negative impacts on operation efficiency* ". On the contrary, the simulations from Harb et al. (2012) showed that when the demand was below 750 vphpl, there was no significant difference between EM and LM in terms of work zone throughput, while at high flow levels EM always produced higher throughputs than LM. One possible reason for this phenomenon given by (Harb et al., 2012) was with the LM control, "*the vehicles do not utilize available gaps between vehicles in the adjacent lanes and wait right till the end to get priority*", but in EM "*lane changing occurs in the transition zone which results in lesser disruptions*".

To understand why the conclusions from these two papers are the opposite of each other, we further checked the VISSIM models they used. An interesting finding was that, besides the differences in the layout of the freeway network, they employed different values for the VISSIM driving behavior parameter: in Yang et al. (2009) the headway time (i.e., VISSIM parameter *CC1*) for EM was 1.7 s and for LM was 1.2 s, but in Harb et al. (2012) a much shorter headway time of 0.5 s was used in all simulations. It is very likely that this VISSIM parameter is a key factor influencing the simulation results and deciding which merge control scheme performs better. To proof this assumption, in this paper we conducted a sensitivity analysis to investigate the impact of the influential parameter(s) (see Section 4).

2.2 Brief description of VISSIM model

VISSIM (Verkehr In Städten – SIMulationsmodell in German) is one of the most widely used traffic simulators with many applications and high potential. It is a microscopic, time step and behavior-based simulation model developed by PTV AG from Germany (PTV, 2012). It is widely used for modeling and analyzing urban and inter-unban traffic, as well as other transport modes (e.g., public transportation, pedestrians, etc.). The most important sub-models in VISSIM are the car-following model and the lane-changing model.

2.2.1 Car-following model

The VISSIM car-following model is based on the Wiedemann's "psycho-physical" driver behavior model (Wiedemann, 1974). The basic concept of this car-following model is when a driver approaches to a slower driver in front, he will decelerate in order to reach a specific safe following distance; however since the driver cannot perfectly estimate the speed difference between him and the preceding vehicle, he could decelerate too much that he moves slower than the preceding vehicle, and hence he will accelerate again in order to keep the safety distance. Therefore, the car-following process in VISSIM is a combination of iterative accelerations and decelerations from vehicles that have different perceptions of desire speed, speed difference, safety distance, as well as the individual characteristics of the driver and vehicle (PTV, 2012). In VISSIM, the Wiedemann 99 model is recommended for the simulation of freeway traffic (PTV, 2012). This model contains 10 parameters which can be configured by the user:

- *CC0*: the standstill distance between two stopped cars. This distance has no variation during the simulation.

- *CC1*: the headway time (in second) for the following vehicle. This is an adjustment factor to control the desire safety distance between two moving vehicles. At a given certain speed v, the safety distance dx_safe is calculated as: $dx\_safe = CC0 + CC1 \times v$. This formula indicates that the higher the value, the longer the distance the driver must keep, and hence a high CC1 refers to cautious driving behavior.

- *CC2*: variation of distance for car following. This parameter controls the longitudinal oscillation in the following process (i.e., the driver follows the vehicle in front without any conscious acceleration or deceleration). During the following process, the distance between two vehicles is within the range dx_safe and $dx\_safe + CC2$.

- *CC3*: threshold that determines when the driver starts to decelerate in order to enter the following process. This parameter defines the time when the deceleration starts before the vehicle reaches the safety distance.

- *CC4* and *CC5*: thresholds that control the speed difference after the vehicle enters the following process. Smaller values of *CC4* (used for negative speed difference) and *CC5* (used for positive speed difference) will make the drivers more sensitive to the acceleration and deceleration of the preceding vehicle.

- *CC6*: parameter that determines the influence of distance on the speed oscillation in the car-following process. When *CC6* is 0, the speed oscillation is independent of the distance to the preceding vehicle, while a high *CC6* will result great speed oscillations in the car-following process.

- *CC7*: acceleration rate during the oscillation process.
- *CC8*: desired acceleration rate when the vehicle starts from standstill. It is limited by the maximum acceleration of the vehicle.
- *CC9*: desired acceleration rate when the vehicle's speed is 80 km/h. It is limited by the maximum acceleration of the vehicle.

As the drivers must keep the minimum distance (i.e., the safety distance) while following the other vehicles, when the traffic demand is high, the parameters such as *CC0*, *CC1* and *CC2* that relate to the safety distance will have a strong impact on the road capacity (PTV, 2012).

2.2.2 Lane-changing model

The lane changes in VISSIM are modeled according to two types: the necessary lane changes and the free lane changes. Drivers make necessary lane changes in order to follow a predefined route (e.g., due to lane closure, intersection), and free lane changes to reach their desired speed or achieve better driving conditions in the adjacent lanes. All lane change decisions are made based on predefined gap acceptance criteria, i.e., the desire to change lane, better driving conditions, as well as the availability of the gap on the adjacent lane.

Necessary lane change behavior is controlled by the vehicle specific parameters, i.e., *maximum deceleration*, *reduction rate of the maximum deceleration*, and *accepted deceleration*. These parameters affect the aggressiveness of the lane changing driver and the trailing vehicle driver. All drivers will first decelerate at their accepted deceleration rates, but if the lane changing driver cannot change lanes within a certain distance before the last mandatory lane change position, the drivers will gradually increase their deceleration rate until they reach their maximum deceleration value. If the driver still cannot change lane at the last mandatory lane change position, he will stop and wait for a possible gap for the lane change. If the stopped lane changing driver is not able to change lanes within a certain period defined by the parameter *waiting time before diffusion*, the vehicle will eventually be removed from the network and recorded as an error. It is not allowed in the current VISSIM to modify the aggressiveness of free lane changes directly. To influence the aggressiveness in free lane changes, the only way is to change the safety distance as defined in the car following model.

Other parameters that influence all lane changes are the *selection of general behavior, minimum headway front/rear*, *Safety Distance Reduction Factor* (*SDRF*), and *maximum deceleration for cooperative braking*. The *general behavior selection* controls the passing rules (e.g. overtaking is only permitted on the left). The *minimum headway front/rear* determines the required minimum distance to the vehicle in front for changing lanes at standstill status. The *SDRF* reduces the safety distance defined in the car-following model for both the leading and trailing vehicle till the lane change maneuver is finished. The *maximum deceleration for cooperative braking* is the greatest deceleration that a trailing vehicle will adopt in order to allow a lane changing vehicle to move into its lane.

To sum up, the aggressiveness of lane change behavior for both necessary and free lane changes is influenced by the safety distance between the leading and trailing vehicles. Therefore the *SDRF*, which takes effect for the safety distance of the trailing and leading vehicle on the desired lane, as well as the distance to the leading vehicle on the current lane, will have a very strong influence on the aggressiveness during all kinds of lane changes.

3. Methodology

3.1 Parameter selection

In VISSIM 5.40 there are around 192 parameters that can be used to simulate all kinds of traffic modes (e.g., cars, trucks, buses, trams, bicycles, pedestrians). To explore the influence of every individual parameter on the simulation results will be a tedious and meaningless work. Therefore in this research we only focused on the parameters having the greatest impact on the work zone capacity in the simulation.

According to the characteristics of this research (e.g., simulation of work zone on freeway, no need for traffic signal control, only cars are modeled, etc.), previous VISSIM calibration studies for freeways (e.g., Gomes et al., 2004; Beacher el al., 2004; Wu et al., 2005; Lownes and Machemehl, 2006), common sense as well as our experiences, we found that the parameters *CC0*, *CC1*, *CC2*, *CC4* and *CC5* from the car-following model and *SDRF* from the lane-changing model can have significant impact on the simulated capacity of the freeway work zone areas.

As mentioned in the last section, the simulated capacity is greatly influenced by the safety distance adopted in the car-following model. As the minimum safety distance is calculated as $dx\_safe = CC0 + CC1 \times v$, it is obvious that when the vehicles are traveling at free-flow speed (e.g., v = 80 km/h), *CC1* will have a much higher impact on the safety distance than *CC0*. In addition, the research done by Chitturi and Benekohal (2008) showed that when *CC1* was above 0.8, the contribution of *CC0* on capacity can be neglected, while a value below 0.8 of *CC1* could cause unrealistic variations of the capacity. Therefore in this study we dropped *CC0* from the parameter set and set the minimum value of *CC1* to 0.9.

According to Chatterjee et al. (2009) the parameters *CC4* and *CC5* did not show statistically significant impact on the capacity when their absolute values were lower than 3.0, and based on their visual interpretation of the simulations, an absolute value of *CC4* and *CC5* higher than 3.0 might yield unreasonable car-following process. Hence we excluded *CC4* and *CC5* from the parameter set in this study as well.

To sum up, parameters *CC1*, *CC2* and *SDRF* were chosen as the influential parameters for further testing. We chose the possible data ranges of the 3 parameters (Table 1) according to Chatterjee et al. (2009) and Harb et al. (2012), while all other parameters were fixed to their default values in all tests.

Table 1 The parameters and their ranges for the sensitivity analysis

#	Parameters	Data Range
1	CC1 (s)	[0.9, 1.8]
2	CC2 (m)	[4, 19]
3	SDRF	[0.15, 0.60]

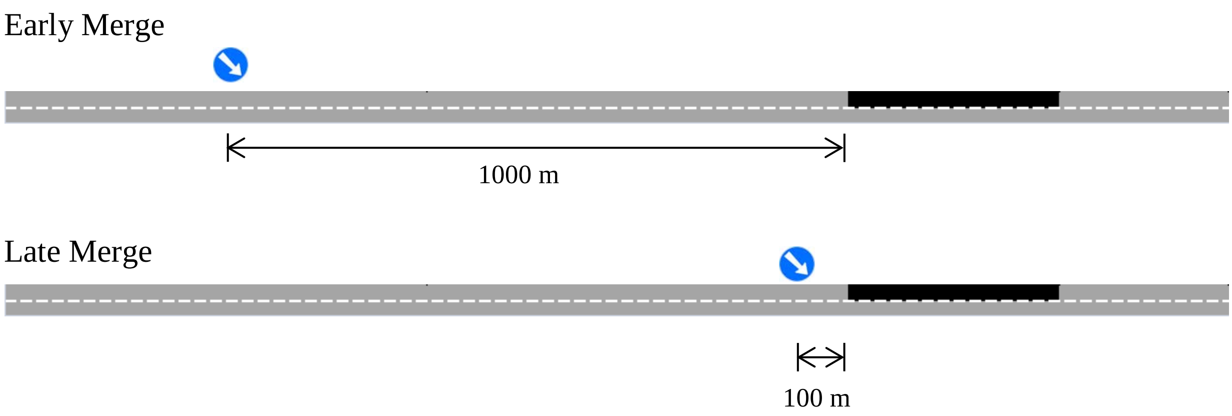
A Sensitivity Analysis (SA) was carried out in order to find out which parameter(s) has the highest influence on the work zone throughput under different traffic demands and the two merge control schemes. For this purpose we employed the quasi-OTEE approach, a qualitative and global SA approach developed by Ge and Menendez (2013), to efficiently measure the relationship between the variation of the input parameters and the relevant outputs. The quasi-OTEE approach uses the Once-At-a-Time (OAT) design and randomly takes values from the possible data range of each parameter in order to generate the model inputs. It calculates the Sensitivity Indexes (SI) based on the Elementary Effects (EE, for details see Saltelli et al., 2008). In general if one parameter has a very high SI, its variation will have a significant impact on the variation of the model results. The SA results are discussed in Section 4.

3.2 Experiment design

In order to investigate the potential benefits of the static EM and LM controls, as well as the most appropriate conditions for applying each control scheme, we designed the experiment for the aforementioned 2-to-1 lane closure work zone scenario in VISSIM. The layouts of EM and LM control are shown in Figure 2.

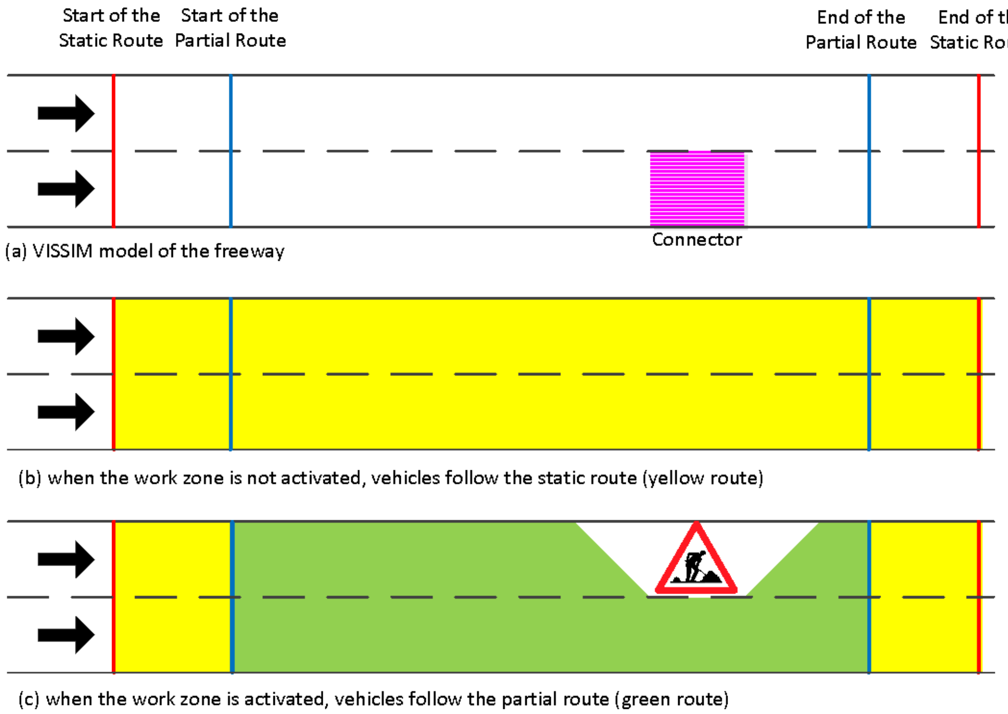
For the EM control scheme, all vehicles are informed to merge into the open lane as soon as they are 1,000 meters upstream of the lane closure; and once they are in the open lane, they are not allowed to reuse the closed lane for overtaking other vehicles until they pass the work zone area. In the LM scenario, the necessary lane change takes place at 100 meters upstream of the work zone; upstream to this point all vehicles can use both lanes to travel or overtake other vehicles freely. The distances used for EM and LM were based on the studies from McCoy et al. (1999) and Pesti et al. (1999). The speed limit control was not included in our simulation, although in real life it is usually implemented together with the merge control upstream of work zone. The reason is to avoid the joint effects from both the speed control and merge control, which cannot be easily separated from the simulation results and may provide incorrect information about the actual impact of the merge control on traffic.

Figure 2 Layout of the EM and LM control schemes



The VISSIM model for the EM and LM control scheme is shown in Figure 3. In this model we used a connector (the pink region in Figure 3a) to connect the upstream and downstream segment of the open lane in the two-lane link. The red marks are used for the static route, and the blue marks are used for the partial route. When the simulation starts, all vehicles will travel along the road by following the static route (the yellow region in Figure 3b), i.e., they will use all lanes to reach their destination. The partial route (the green region in Figure 3c) will take effect when work zone is activated. As the partial route is located inside the static route, it will direct all traffic over the predefined connector to pass the work zone area. The distance at which the vehicles are suggested to start merging is defined by the parameter *Lane Change* of the connector. For example, for the EM control scheme, this parameter was set to 1,000 m in the simulation according to the layout of EM in Figure 2.

Figure 3 Layout of the EM and LM controls in VISSIM



The percentage of trucks in all simulations was set to 10% of the total traffic. The desired speed was 100 km/h for cars and 80 km/h for trucks. The Wiedemann 99 car-following model was used to replicate the freeway driving behavior. Every simulation was run for 3,000 s, including a warm up time of 1,200 s, i.e., the activation of the work zone started at 1,200 s in the simulation. To investigate the performance of EM and LM controls under different traffic demands conditions, the vehicle inputs in the simulation were set to range from 2,000 veh/h to 4,000 veh/h at an increment of 500 veh/h.

The sensitivity analysis for all scenarios was based on the 30-minute (i.e., from 1,200 s to 3,000 s) traffic counts measured downstream of the work zone area. According to the SA results, we picked the parameter(s) that influenced most the throughput in both merge control schemes. Then based on different values of the influential parameters, the work zone capacities and queue lengths were compared in the scenarios with the EM and LM control schemes (for details see Section 4.2). In addition, the trajectory data for every single vehicle was recorded from the activation of the work zone in order to further support the performance comparison.

4. Results

4.1 Sensitivity analysis results

As mentioned above, the quasi-OTEE approach (Ge and Menendez, 2013) was employed for the SA in this study. For each scenario with a specific traffic demand and merge control scheme, we used 100 random quasi-Optimize Trajectories (each trajectory contains 4 sampling points in the input space) for the data sampling. We ran the simulation 400 times with different value combinations of the three parameters *CC1*, *CC2* and *SDRF* for each scenario. Five independent simulations using different VISSIM random seeds were carried out for every scenario to produce convincing results.

We adopt the absolute mean of the Elementary Effects, i.e., $\mu*$, to compare the impacts of the three VISSIM parameters on the simulated work zone throughput under different traffic demands for the two merge control schemes. The results are shown in Figure 4. It should be noted that in Figure 4 any particular value/scale of $\mu*$ is not important because it is context dependent (Morris, 1991), i.e., the value will change when using different metrics for the measurement. On the contrary, we should focus on their relative differences according to the principle of the quasi-OTEE approach (Ge and Menendez, 2013). As a general rule, a relative high $\mu*$ indicates that the variation from the corresponding parameter can cause significantly larger variation for the results than the other parameters.

Figure 4 SA results for the 30-min throughput for EM and LM under different demands

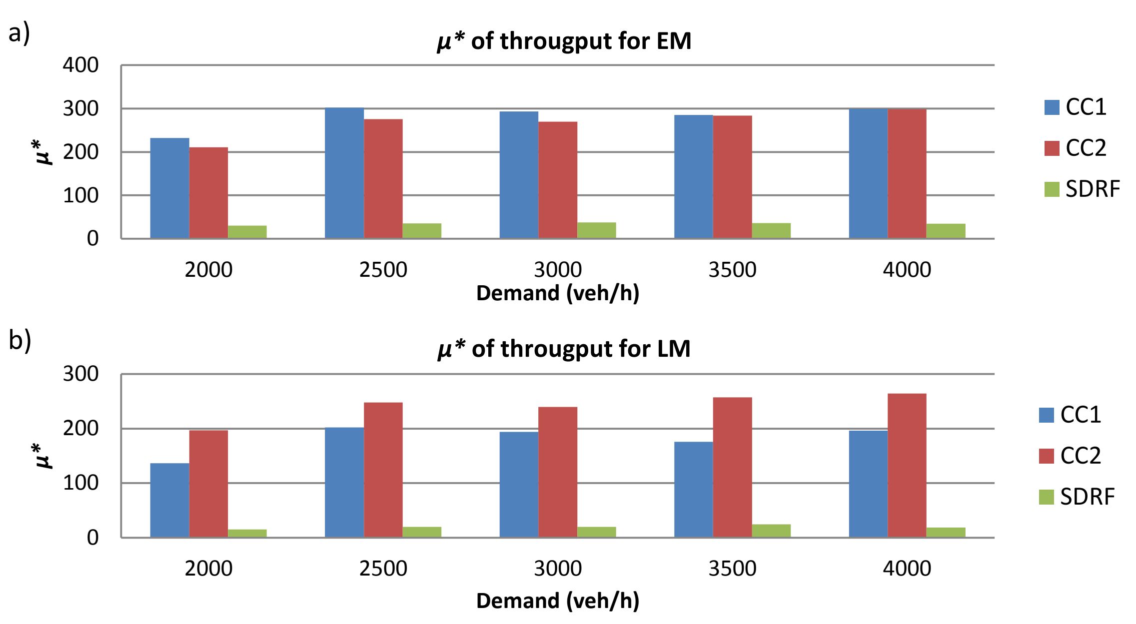


Figure 4 clearly shows that parameters *CC1* and *CC2* have a much higher $\mu*$ than the parameter *SDRF* across all scenarios. It indicates that the parameters *CC1* and *CC2* are more influential than the parameter *SDRF*, independently of the adopted merge control scheme and the traffic demand. This also shows that the variance from the safety distance defined in the VISSIM car-following model has a great contribution to the variance of the work zone throughput.

To extensively investigate the impact of adjusting *CC1* and *CC2* on the work zone throughput, we compared the $\mu*$ with μ, which is the mean value of the EE, under different demands and control schemes (Table 2). It is shown in Figure 2 that with a certain traffic demand and merge control scheme, the absolute values of $\mu*$ and μ are exactly the same, while the only difference is $\mu*$ is always positive and μ is always negative. According to the definition of EE, this indicates that under all conditions, the increase of *CC1* and *CC2* will always cause the decrease of work zone throughput. The decrease is monotonic, otherwise the absolute value of μ should be smaller than $\mu*$.

This phenomenon can be explained with traffic flow theory as well: the parameters *CC1* and *CC2* are related to the safety distance between two consecutive vehicles in the simulation. The increase of *CC1* and *CC2* will produce larger gaps on the road, i.e., larger spacing. Thus, within a certain road section the number of vehicles is reduced, i.e., the density is reduced. In the simulation, the maximum flow q that can pass the work zone is calculated as the product of the desired speed v and the road density k. When *CC1* and *CC2* get increased and v remains unchanged, the flow q will drop because the decrease of k.

Table 2 The $\mu*$ and μ of *CC1* and *CC2* under different demands and merge schemes

		EM					LM				
	Demand	2000	2500	3000	3500	4000	2000	2500	3000	3500	4000
CC1	$\mu*$	232	302	294	285	299	136	202	194	176	196
	μ	-232	-302	-294	-285	-299	-136	-202	-194	-176	-196
CC2	$\mu*$	211	275	270	284	298	197	248	240	257	264
	μ	-211	-275	-270	-284	-298	-197	-248	-240	-257	-264

Moreover, we cross compared the $\mu*$ of *CC1* and *CC2* derived from the EM scheme (Figure 3a) and the LM scheme (Figure 3b) under the same demand level. It is found that there is no significant difference of the $\mu*$ of *CC2* between EM and LM, while the $\mu*$ of *CC1* in all EM scenarios are much higher than the corresponding ones in all LM scenarios. This means that increasing *CC2* may cause almost the same reduction of throughput in both EM and LM control schemes, but increasing *CC1* will produce different results: the decrease of throughput is much more significant in the EM scenario than in the LM scenario. In other words, it is possible that in the simulation with a small *CC1*, EM can outperform LM in terms of greater throughput, but along with the increase of *CC1*, since the throughput in the EM scenario drops faster than that in the LM scenario, the LM can perform better than EM when *CC1* reaches a certain high value. This assumption is proofed with our simulation results in the next section.

4.2 Simulation results

4.2.1 Work zone capacity

Since the road capacity cannot be directly defined in VISSIM, in order to compare the work zone capacity with the EM and LM controls, we measured the capacity data by gradually increasing the traffic demand and comparing the corresponding throughput. It was determined in the SA that *CC1* is a critical parameter for the capacity measurement: increasing *CC1* can cause monotonic decrease of the work zone throughput, and the decreasing rate in the EM scenario is always higher than that in the LM scenario. To investigate the work zone capacity and take the impact of *CC1* into account, we chose 6 samples (Table 3) of the parameters *CC1*, *CC2* and *SDRF* that were already generated in the SA process: three of them used the high value of *CC1* (i.e., 0.9 s), and the other three adopt the low value of *CC1* (i.e., 1.8 s). In addition, as the safety distance in VISSIM could oscillate in the interval [$CC0 + CC1 \times v$, $CC0 + CC1 \times v + CC2$], in order to minimize the capacity oscillation caused by *CC2*, *CC2* was set to the lowest value (i.e., 4 m) in all scenarios.

Table 3 Parameter set used for measuring the work zone capacity

Parameter Set	CC1	CC2	SDRF
1	0.9	4	0.24
2	0.9	4	0.42
3	0.9	4	0.60
4	1.8	4	0.24
5	1.8	4	0.42
6	1.8	4	0.60

For each parameter set, we reran all simulations under the traffic demands ranged from 1,000 veh/h to 4,000 veh/h at an increment of 100 veh/h. The 30-min work zone throughput under each demand level was recorded and converted to the hourly throughput in each scenario. Then for every scenario with a certain merge control scheme and parameter set, we sequentially compared the hourly throughputs derived from the lowest demand level to the highest demand level. Once the relative difference between two consecutive throughputs was less than 0.01, we assumed that the corresponding demand just crossed the work zone capacity in this scenario. We recorded such demand as well as other higher demands. The mean of the respective throughputs under these demands was regarded as the work zone capacity for this specific scenario. The results are shown in Table 4.

Table 4 Capacity for each simulation scenario

Parameter Set	EM Capacity (veh/h)	LM Capacity (veh/h)	Difference (veh/h)
1	2441	2257	184
2	2434	2231	203
3	2404	2196	208
4	1729	1827	-98
5	1702	1807	-105
6	1666	1776	-110

Table 4 shows that the value of *CC1* can significantly influence the results of capacity comparison between EM and LM: when the value of *CC1* is low (e.g., 0.9), the work zone with the EM control has a higher capacity than that with the LM control; conversely, when the value of *CC1* is high (e.g., 1.8), the capacity of LM controlled work zone is slightly higher.

A possible reason for such phenomenon is that when vehicles merge far away from the work zone (i.e., EM), the speed does not drop much; on the contrary when vehicles merge very close to the work zone (i.e., LM), there is a greater reduction of the speed. Therefore, the speed in the merge area is usually higher in the EM scenario than in the LM scenario area. In VISSIM the minimum safety distance is $CC0 + CC1 \times v$, and *CC0* is a constant. Since the speed v is higher in EM than in LM, the increase of *CC1* will bring a higher increase of the minimum safety distance in the EM scenario than in the LM scenario. As a result the density in the EM scenario drops faster than that in the LM scenario, and so does the throughput in the EM scenario. When *CC1* reaches a certain high value (e.g., 1.8), it is possible that the throughput in EM drops too much so that the throughput in LM is even higher.

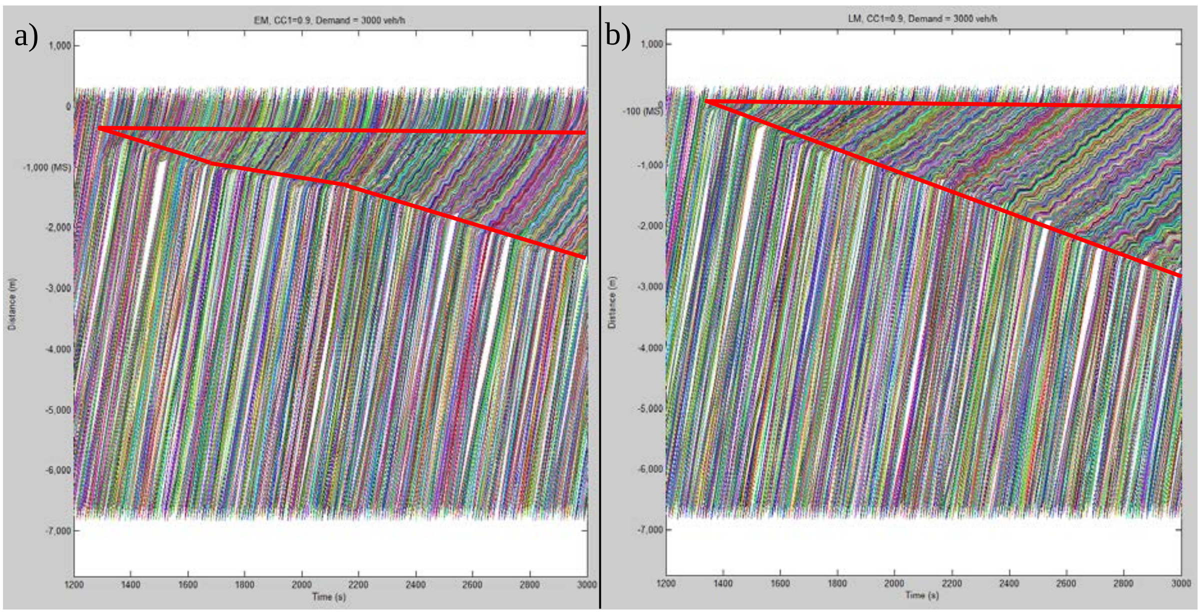
The impacts from *CC1* on the work zone capacity can somehow explain why Yang et al. (2009) and Harb et al. (2012) derived conflicting results as reviewed in Section 2.1. In (Yang et al., 2009) the value of *CC1* was set to 1.7 for the EM scenario and 1.2 for the LM scenarios. As mentioned above, increasing *CC1* will monotonically decrease the work zone throughput, therefore when *CC1* = 1.7, the capacity of LM controlled work zone (i.e., $C_{LM,\ CC1\ =\ 1.7}$) is lower than $C_{LM,\ CC1\ =\ 1.2}$, but higher than $C_{EM,\ CC1\ =\ 1.7}$, as 1.7 is a rather high value for *CC1*. In other words, the inequality $C_{LM,\ CC1\ =\ 1.2} > C_{LM,\ CC1\ =\ 1.7} > C_{EM,\ CC1\ =\ 1.7}$ is true. Therefore, it is not a surprise that in (Yang et al., 2009) the throughput with the LM control could be higher than that with the EM control. In the paper written by Harb et al. (2012), *CC1* was set to 0.5 in all simulations. According to the aforementioned *CC1*'s characteristic, a relatively low value of *CC1* can make the work zone capacity higher with the EM control than with the LM control, and that is consistent with the findings in (Harb et al., 2012).

4.2.2 Queue length

The queue length under different merge control schemes can be interpreted from the time-space diagram. Here the trajectory data derived from the Parameter Sets 1 and 4, demand of 3,000 veh/h is used to draw the time-space diagram (Figures 5 and 6). It should be noted that similar patterns can be found in the time-space diagrams derived from other trajectory data sets.

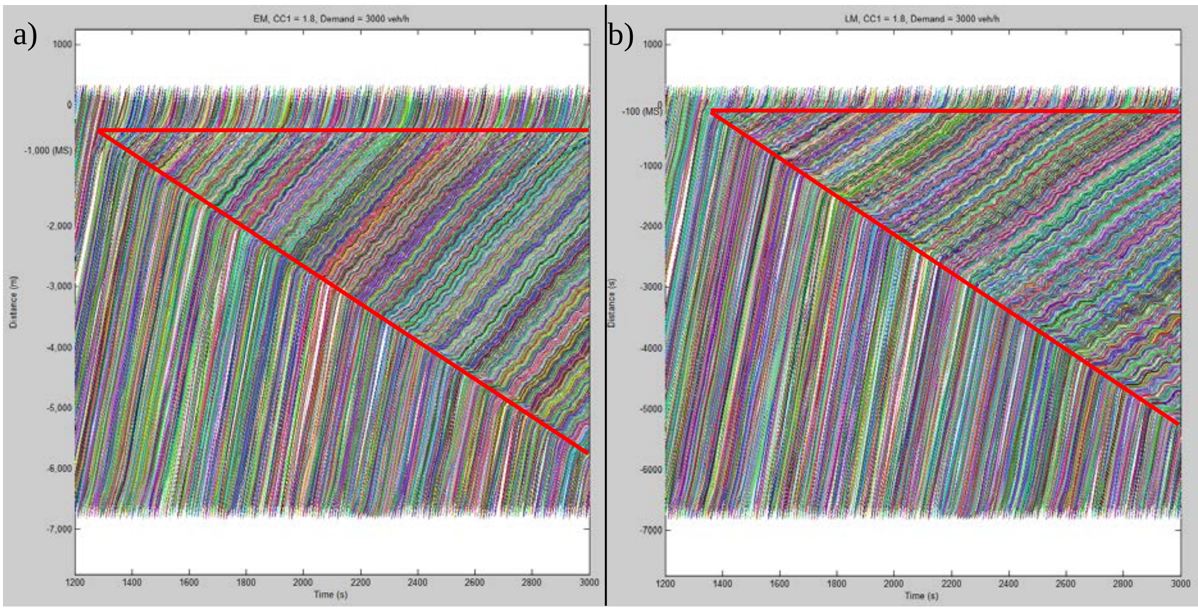
In Figure 5, the queue forms earlier in the EM scenario (around 1,300 s) than in the LM scenario (around 1,360 s). However, at the end of simulation (i.e., 3,000 s), the EM scenario has a much shorter queue (around 2,145 m) than the LM scenario (around 2,688 m). This shows that the queue grows much slower in the EM scenario (around 1.26 m/s) than in the LM scenario (around 1.63 m/s) when *CC1* is low.

Figure 5 Time-space diagram using Parameter Set 1 (*CC1* = 0.9), demand = 3,000 veh/h



In Figure 6, the formation of the queue also starts earlier in the EM scenario (around 1,310 s) than in the LM scenario (around 1,350 s). However, at the end the queue in the LM scenario (around 5,222 m) is slightly shorter than in the EM scenario (around 5,387 m). Therefore, when *CC1* is high, the queue grows slightly faster in the EM scenario (around 3.18 m/s) than in the LM scenario (3.16 m/s).

Figure 6 Time-space diagram using Parameter Set 4 (*CC1* = 1.8), demand = 3,000 veh/h



The time-space diagrams show that in all EM control scenarios the queue appears earlier than in the LM control scenarios, therefore one benefit of LM control is the delay of queue formation. In addition, when the drivers are aggressive and the minimum safety distances between two vehicles are small (i.e., *CC1* is low), implementing the EM control will gain benefits from shorter queue length as the queue grows much faster with the LM control. In contrast, when the drivers are quite cautious and always keep long distances to the front vehicles (i.e., *CC1* is high), implementing the EM control is not recommended as the queue will grow slower with the LM control, and LM control offers a higher capacity and delays the queue formation.

5. Conclusions

In this study we used the microscopic traffic simulator VISSIM to investigate the performance of two merge control schemes, i.e., static EM and LM, for a 2-to-1 lane closure work zone on freeway. A sensitivity analysis was carried out in order to detect the most influential VISSIM parameters with respect to the work zone throughput. It is found that the parameters *CC1* and

CC2 from the car-following model are more influential than the parameter *SDRF* from the lane-changing model, and increasing *CC1* and *CC2* in the simulation can significantly cause monotonic decrease of the work zone throughput. Furthermore, the SA results indicate that the parameter *CC1* is a very critical parameter for the simulations with the EM and LM controls: when increasing *CC1*, the work zone throughput decreases faster in the EM scenario than in the LM scenario.

The work zone capacity test shows that when *CC1* has a low value, the work zone with the EM control has greater capacity than that with the LM control; on the contrary, when *CC1* is at a high value, the LM control scheme outperforms the EM control schemes in terms of higher capacity. This also indicates that using different values of *CC1* can drive totally different simulation results for the work zone throughput (e.g., Yang et al. (2009) versus Harb et al. (2012)). Therefore to avoid inaccurate results in the VISSIM-based merge control studies, the driving behavior parameter *CC1* should be carefully calibrated and validated according to the field data.

Furthermore, the simulations show that it is more appropriate to implement the EM control when the drivers are aggressive and the safety distance is relatively short (i.e., *CC1* is low). The reason is that under such condition the work zone using the EM control can have a higher capacity slowing the queue formation. In contrast, when the drivers are cautious and the safety distance is relatively long (i.e., *CC1* is high), it is better to implement the LM control as it offers a higher capacity and delays the formation of the queue.

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