



New England merge: a novel cooperative merge control method for improving highway work zone mobility and safety

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ABSTRACT

Given the aging infrastructure and the anticipated growing number of highway work zones in the United States, it is important to investigate methods to improve work zone mobility and safety. Data suggests that inappropriate merge maneuvers are a major contributing factor to highway work zone crashes that often lead to severe congestion and delay. This research proposes a New England Merge (NEM) for highway work zone control, which requires vehicles to behave cooperatively and create safe merging gaps when approaching lane closure points caused by work zones. Based on VISSIM microscopic simulations considering varying input traffic demands, the NEM is compared with late merge, early merge, and no control in terms of average delay, mean travel time, and throughput. Additionally, the safety performance of NEM is analyzed using surrogate safety measures such as vehicle trajectory, density, acceleration, and distance headway. A typical type of highway work zone is modeled in this study, which represents a two-lane highway with the right lane closed. The modeling results show that overall NEM significantly outperforms all other merge control methods in terms of both safety and mobility measures. Similar to late merge and early merge, implementing the NEM would benefit from driver cooperation. The applicability of NEM can be substantially improved with the wide adoption of cooperative adaptive cruise control (i.e., level 1 automation) technology.

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Introduction

In the 2017 American Society of Civil Engineers (ASCE) infrastructure report card (ASCE, 2017), America's infrastructure received an overall rating of "D+". It was estimated that nearly \$4.6 trillion is needed by 2025 to fix the infrastructure problems. It is anticipated that there will be many work zones in the coming years due to highway and bridge construction and maintenance activities. Work zones often require lane/shoulder closure or lane shift that lead to traffic congestion and increased crash risk, particularly rear-end and angle crashes due to stop-and-go traffic and unsafe merge behaviors. Work zone crashes result in approximately \$8.66 billion loss each year due to fatalities, injuries, and property damage (Mohan & Gautam, 2000). Therefore, work zone safety and mobility have attracted much attention in the past few decades.

Data suggests that inappropriate merge behaviors are a major contributing factor to work zone crashes (Xie et al., 2018), causing severe congestion and delay.

Many previous work zone studies are focused on merge control and proposed a variety of strategies such as early merge (EM) and late merge (LM). As illustrated in Figure 1, EM (Beacher et al., 2004; Tarko et al., 1998) typically uses a sequence of "DO NOT PASS" signs that can be activated/deactivated depending on traffic to create a no passing zone of varying length. A traffic sensor is mounted on each sign to monitor the traffic. The purpose of the no passing zone is to encourage drivers to switch to the open lane upstream of the end of the dynamically changing queue to improve safety and efficiency. While for LM, drivers in both the open and closed lanes are urged to stay in their respective lanes until the merge point, where they take turns to merge as shown in Figure 2.

Early merge was found to be able to reduce risky late merge behaviors and improve the travel speed in the open lane (Tarko et al., 1998). It is recommended that adequate law enforcements should be provided to ensure drivers follow the "DO NOT PASS" sign.

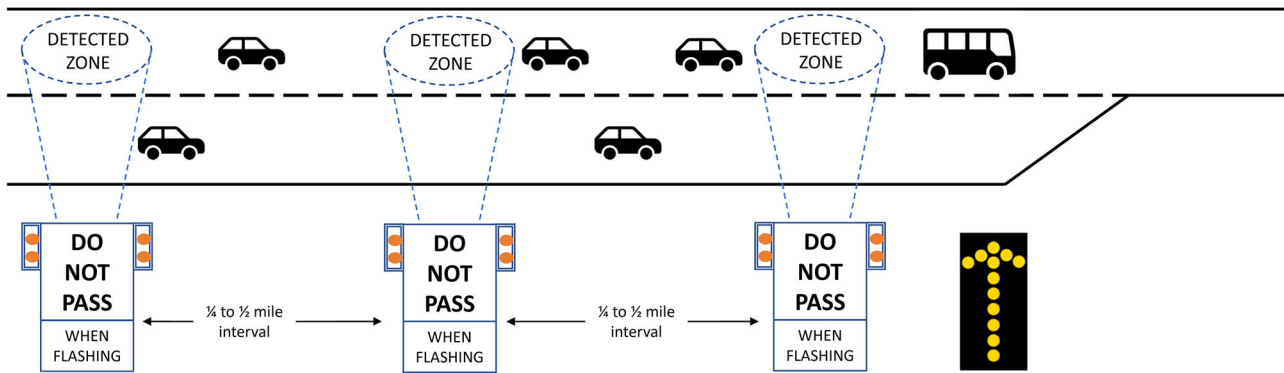


Figure 1. Early merge for work zones (Beacher et al., 2004).

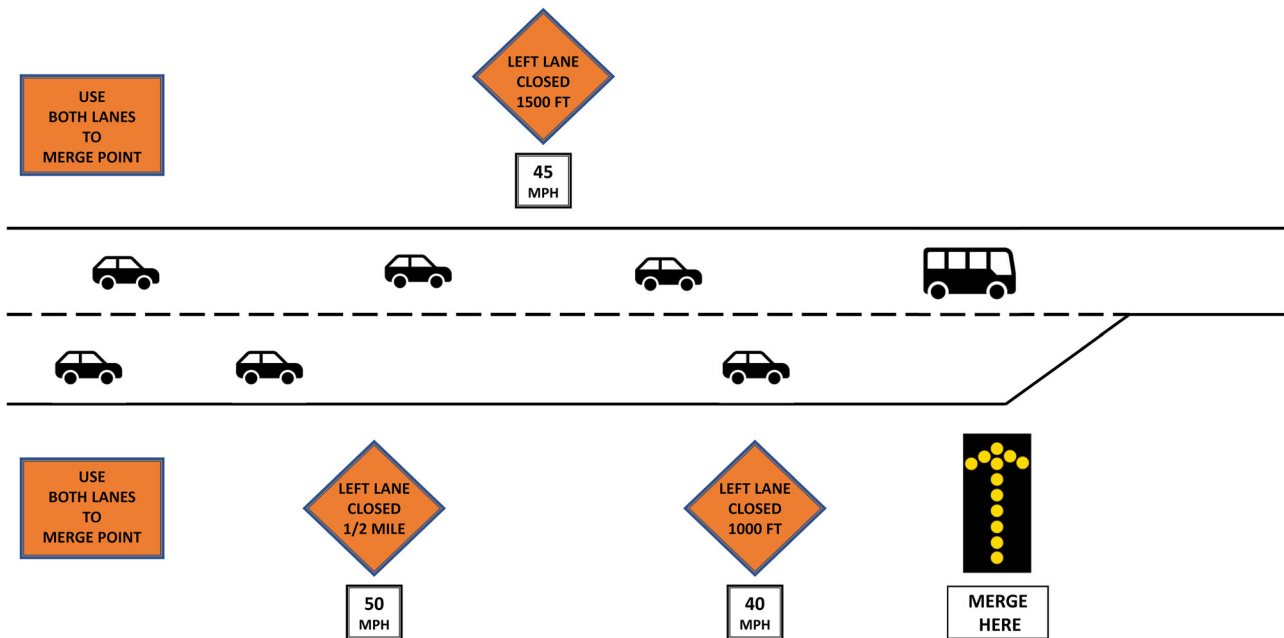


Figure 2. Late merge for work zones (Beacher et al., 2004).

Kurker et al. (2014) noted that the compliance rate of early merge drops as congestion builds up. This may subsequently affect its mobility and safety performance. If early merge is not properly set up/operated either due to inadequate sign coverage/law enforcement, low compliance rate, or queue spills back beyond “DO NOT PASS” signs, aggressive driving behaviors such as queue jumping, lane straddling, and forced merge may happen, which are extremely dangerous. Late merge can better address these issues along the approach to the merging point. However, at the merging point the take-turn-to-merge rule may create both risky short gaps (due to limited merge distance) and inefficient large gaps (due to the slow movement/acceleration of heavy vehicles) that affect safety and throughput. To fully benefit from the potential of late merge, Pesti et al. (1999) suggested that efforts should be taken to familiarize drivers with the “TAKE TURN” to merge rule.

Some studies suggested that early merge performs better under light traffic conditions (Kurker et al., 2014; Pesti et al., 2008; Tarko & Venugopal, 2001), and late merge is better for moderate to heavy traffic conditions. However, other studies have reached inconsistent conclusions (McCoy et al., 1999; Tarko et al., 1998). In particular, Ramadan and Sisiopiku (2016) found late merge to outperform early merge under off-peak conditions as well based on simulations. In another field study, Harb et al. (2011) found early merge to generate higher throughputs than late merge under uncongested conditions. Also, Meyer (2004) concluded that late merge does not necessarily provide higher capacity than early merge. He recommended a set of overlapping speed threshold values to switch between early and late merges to avoid oscillation. This overlapping strategy was also considered by Kang et al. (2006). Other than early merge and late merge, Rayaprolu et al. (2013) proposed a joint lane

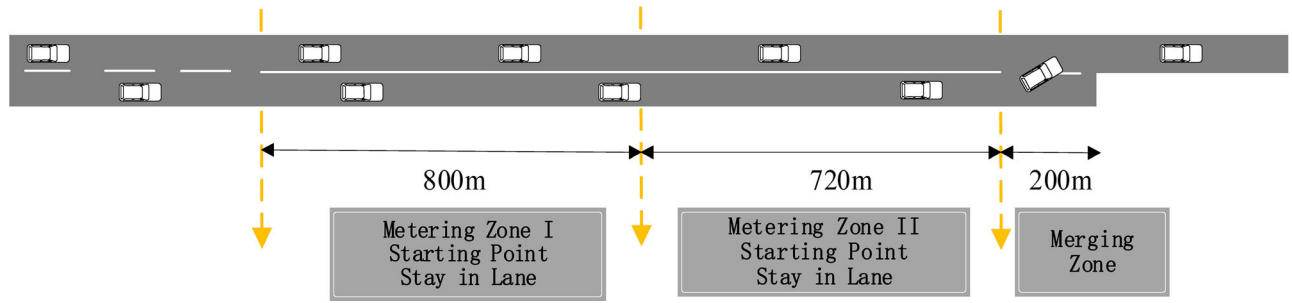


Figure 3. Overview of NEM control.

merge strategy for two-lane highway work zones with one lane closed. The joint lane merge uses a transition area to provide both the open and closed lanes equal right of way to merge, instead of favoring the open lane over the closed lane as in most traditional work zone configurations. This method can facilitate the implementation of late merge. However, it does not include any explicit strategies to address the above-mentioned issues (i.e., short and large gaps) associated with late merge and to generate high-density and high-speed flow at the merging point.

As discussed above, each of the existing popular merge control methods has certain major limitations and how to improve work zone mobility and safety remains a challenging task. In this research, a new merge control method, New England Merge (NEM), is proposed. Unlike early and late merge controls, the NEM is intended for a wide range of traffic demand conditions, and there is no need to frequently switch work zone merge control strategies in response to changes in traffic arrivals (Kang et al., 2006; Meyer, 2004). The NEM leverages the potential benefits of Connected and Autonomous Vehicles (CAV) for work zone traffic operations. Its applicability can be substantially improved with the wide adoption of Cooperative Adaptive Cruise Control (CACC), which is a crucial level 1 vehicle automation technology. The proposed NEM strategy and algorithm are evaluated using VISSIM simulation, and compared with commonly-used work zone merge control strategies such as early merge, late merge, and no-control merge. These control strategies are compared based on both mobility and safety measures under various traffic demand levels. In the following section, the NEM is presented.

Methodology

Overview

As shown in Figure 3, In NEM the approach to a work zone is divided into two metering zones followed

by a merging zone. Vehicles approaching the work zone are instructed to increase their distance headways upon entering Metering Zone I. Specifically, each vehicle needs to increase its front distance headway to twice the safe distance needed for the corresponding speed (70 km/h). Metering Zone I is to provide sufficient distance for vehicles to adjust their front gaps and lane change is prohibited in this zone. In Metering Zone II, vehicles in the open lane (left lane in Figure 3) will adopt the same car-following behavior as in Metering Zone I, while vehicles in the closed lane (right lane in Figure 3) are asked to adjust their longitudinal positions so that they travel near the middle point of two consecutive vehicles in the adjacent left lane. Following this longitudinal control strategy, toward the end of Metering Zone II, if vehicles in both lanes are projected onto a single virtual lane, all the distance headways are expected to be close to but greater than the safe distance gap required. In the merging zone, lane changes are allowed and vehicles in the two lanes take turns to merge. In summary, the core of NEM is the longitudinal control in the two metering zones, where lane changes are prohibited. Before Metering Zone I, vehicles follow normal driving behavior. After Metering Zone II, vehicles also follow normal driving behavior other than being instructed to merge in the merging zone.

In this study, the NEM strategy and other benchmark strategies are all evaluated using VISSIM microscopic traffic simulation. Vehicles before and after the two metering zones are assumed to be controlled by the default car-following model in VISSIM. Therefore, to better describe the NEM strategy, the VISSIM Wiedemann 99 car-following model and variables used in it are briefly described below

Definitions of variables

The following variables are used in both the VISSIM Wiedemann 99 car-following model and the proposed NEM control strategy:

- CC0 : Standstill Distance (Desired distance between the lead and following vehicles when both vehicles' speeds equal 0);
- CC1 : Headway Time (Desired time in seconds between the lead and following vehicles);
- CC2 : Following Variation (Additional distance beyond safety distance that the following vehicle requires);
- CC3 : Perception threshold for following (Defines the beginning of the deceleration process);
- CC4 : Negative speed difference (A low value leads to a more sensitive subject vehicle driver reaction to the lead vehicle);
- d_x : distance gap between the lead and following vehicles measured in meters, which is calculated as lead vehicle front bump distance - lead vehicle length;
- acc : Vehicle acceleration rate measured in meters/s²; and
- v : vehicle speed measured in meters/s.

VISSIM car-following model

In the Wiedemann 99 model (Aghabayk et al., 2013; PTV AG, 2020), vehicles' distance keeping behavior and the related parameters and thresholds are defined in Eqs. (1)–(4).

$$d_s = L + CC0 \quad (1)$$

where d_s is the desired distance between two stationary vehicles, and L is the length of the lead vehicle.

$$d_{fl} = d_s + CC1 \cdot v \quad (2)$$

where d_{fl} is the minimum safe distance. v equals the lead vehicle's speed with some random errors if the subject/following vehicle is faster than the lead vehicle, otherwise v equals the subject vehicle's speed.

$$d_{fu} = d_{fl} + CC2 \quad (3)$$

In Eq. (3), d_{fu} is the upper bound of safe distance indicating the boundary between the “no reaction” and “unconscious reaction/following” states. When the subject vehicle enters the “unconscious reaction/following” state (i.e., distance between them is $< d_{fu}$), the acceleration of the subject vehicle will oscillate around 0.

$$d_r = -\frac{\Delta x - d_{fu}}{CC3} - CC4 \quad (4)$$

d_r in Eq. (4) defines the perception threshold distance between the lead and subject vehicles. It determines if the subject vehicle is in the “reaction/approaching” state. Δx is the front bump to front bump distance between the two vehicles. When the subject vehicle enters the “reaction/approaching” state (i.e., distance between them is $< d_r$), the subject vehicle will begin to decelerate.

NEM control

As discussed above, the core of NEM is the longitudinal control in the two metering zones. Based on the above variables and the Wiedemann 99 model, the longitudinal control algorithms in the two metering zones are described separately below.

Longitudinal control in metering zone I

In Metering Zone I, all vehicles in the open lane are instructed to increase front gaps with their lead vehicles. In Metering Zone II, vehicles in the closed lane further adjust their positions to travel in the middle of the created gaps in the open lane. In this way, in the merging zone vehicles in the closed lane can easily move into the open lane without obstructing vehicles in it. The following equations describe how gaps should be increased for vehicles in the open lane. Based on the Wiedemann 99 car-following model, the distance headway between two consecutive vehicles in the left (open) lane (Figure 4) should satisfy the condition in Eq. (5) to ensure safety at and beyond the merging point.

$$d_{x1} \geq d_{x2} + l_2 + d_{x3} \quad (5)$$

where d_{x1} is the safe distance between two vehicles in the left lane, and l_2 is the length of the subject vehicle in the closed lane. Following the Wiedemann 99 car-following formulation, the minimum opening distance for vehicles in the open (left) lane is calculated using Eq. (6), where $CC1_{open}$ is the headway time that the NEM strategy should consider in Metering Zone I. This headway time naturally should be larger than what is normally needed to open up gaps for merging

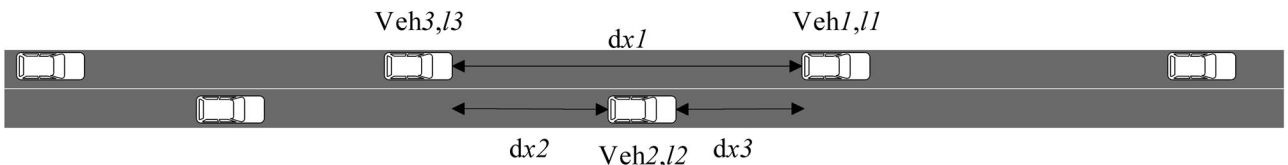


Figure 4. Longitudinal control in Metering Zone I.

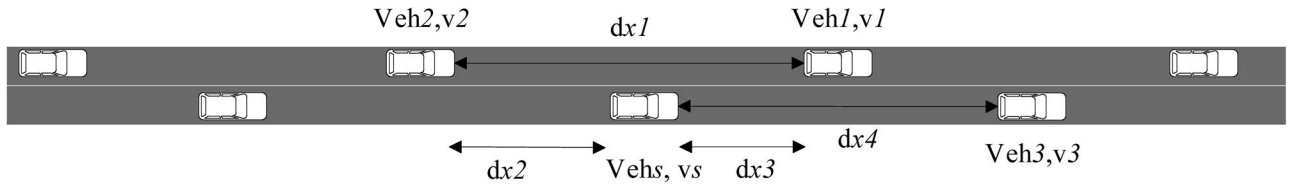


Figure 5. First case for longitudinal control in Metering Zone II.

vehicles from the closed lane. Equation (7) shows how to calculate the minimum opening distance for vehicles in the closed lane in Metering Zone I, which takes vehicles (i.e., Veh₁ and Veh₃) in the open lane into consideration. This is because in Metering Zone II vehicles in the closed lane need to adjust their longitudinal positions so that they travel in the middle of a gap created by consecutive vehicles in the open lane. In Eq. (7), CC1_{closed} equals the default CC1 in the Wiedemann 99 car-following model.

$$d_{x1} = CC0 + CC1_{open} * v + CC2 \quad (6)$$

$$d_{x2} = dx3 \geq CC0 + CC1_{closed} * v + CC2 \quad (7)$$

In both Eqs. (6) and (7), v is set to 20.1 m/s (45 mph), which is often enforced in highway work zones. In addition, CC0 is set to 1.5 meters, CC1_{closed} = 1.7 seconds, and CC2 = 4 meters based on VISSIM manual. According to Eqs. (5)–(7), the headway time CC1_{open} for vehicles in the open lane of Metering Zone I should be set to

$$\begin{aligned} CC1_{open} &\geq \frac{l_2 + CC0 + 2 * CC1_{closed} * v + CC2}{v} \\ &= 3.81 \text{ seconds} \end{aligned} \quad (8)$$

To ensure safety, this study uses 3.9 seconds for CC1_{open} in VISSIM. This CC1_{open} applies to vehicles in the open lane throughout the two metering zones. While for vehicles in the right (closed) lane of the two metering zones, their CC1_{closed} is set to 1.7 seconds. Note that when calculating the accelerations for vehicles in the closed lane, the positions of adjacent vehicles (i.e., Veh₁ and Veh₃) in the open lane are taken into consideration as illustrated in Figure 4.

Longitudinal control in metering zone II

As mentioned earlier, to maximize the throughput at the merging point vehicles in the closed lane should stay in the middle of a gap generated by two consecutive vehicles in open lane. Two cases need to be addressed separately. The first case is for $d_{x4} \geq d_{x3}$. As shown in Figure 5, between the two consecutive vehicles in the left open lane (i.e., Veh₁ and Veh₂), there are no lead vehicles in front of the subject vehicle (i.e., Veh_s). This case is further divided into

four scenarios. The acceleration rates of the subject vehicle (Veh_s) under each scenario are determined by the following Eqs. (9)–(12).

1. If $d_{x3} > d_{x2}$ and $vs > (v1 + v2)/2 + 3$:

$$acc = \max\left(-\sqrt{d_{x2}2}, \frac{v1 + v2}{2} - vs\right) \quad (9)$$

2. If $d_{x3} > d_{x2}$ and $vs \leq (v1 + v2)/2 + 3$:

$$acc = \min(\sqrt{d_{x3} - d_{x2}2}, 2) \quad (10)$$

3. If $d_{x3} \leq d_{x2}$ and $vs < (v1 + v2)/2$:

$$acc = \min\left(-\sqrt{\frac{(d_{x2} - d_{x3})}{2}2}, \frac{v1 + v2}{2} - vs\right) \quad (11)$$

4. If $d_{x3} \leq d_{x2}$ and $vs \geq (v1 + v2)/2$:

$$acc = \max(-\sqrt{d_{x2} - d_{x3}2}, -2) \quad (12)$$

The second case is for $d_{x4} < d_{x3}$. As illustrated in Figure 6, between the two consecutive vehicles in the left open lane (i.e., Veh₁ and Veh₂), there are other vehicles in front of the subject vehicle (i.e., Veh_s) in the closed lane. This case similarly is further divided into two scenarios. The acceleration rates of the subject vehicle (Veh_s) under each scenario are determined by the following Eqs. (13) and (14).

1. If $d_{x2} + d_{x4} \geq 2 * d_{xu}$ (CC1 = 1.7)

$$acc = \text{Wiedemann}(CC1 = 1.7) \quad (13)$$

2. If $d_{x2} + d_{x4} < 2 * d_{xu}$ (CC1 = 1.7)

$$acc = \text{Wiedemann}(CC1 = 10) \quad (14)$$

Wiedemann(CC1 = 10) means the subject vehicle's acceleration is calculated using the Wiedemann 99 model with CC1 = 10. Equation (13) implies that when the gap ($d_{x2} + d_{x4}$) is large enough to allow the subject vehicle (Veh_s) to merge downstream without affecting vehicles in the open lane, the subject vehicle (Veh_s) will adopt the default Wiedemann 99 model for car-following behavior. When the gap is insufficient, the subject vehicle will

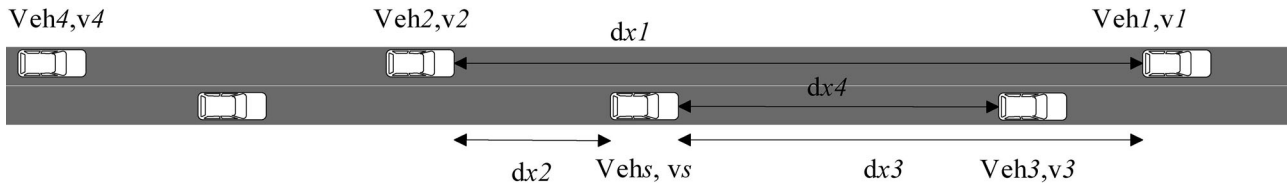


Figure 6. Second case for longitudinal control in Metering Zone II.

adopt a modified Wiedemann 99 model with a large CC1 value. This large value (i.e., $CC1 = 10$) will cause the subject vehicle to decelerate. In many cases, this will lead to it being the first vehicle in the gap between Veh₄ and Veh₂ in the closed lane (see Figure 6).

Simulation analysis

Experiment design

As in many previous studies, this research adopts a microscopic simulation tool to evaluate the performance of the proposed NEM. The DriverModel dynamic-link library in VISSIM is used to implement the NEM strategy. NEM is simulated using VISSIM and compared with EM, LM and no control (base case) under various input traffic volumes. In this research, the min headway and headway time parameters calibrated by Yang et al. (2009) is adopted. For the remaining parameters, the default values in VISSIM are considered. As shown in Figure 3, a work zone on a two-lane highway with the right lane closed is considered. For this work zone, the input traffic volume varies from 1,200 vph to 2,000 vph with an increment of 400 vph. For all simulations conducted, the percentage of heavy vehicles is set to 3%, and the speed limit is set as 70 km/h. For each merge control and input volume combination, the simulation is run 10 times with different random seeds. Each simulation run lasts 45 minutes with the first 15 minutes serving as the warm-up period.

Overall mobility performance

Table 1 shows the mobility performance for different control strategies under three input traffic volumes. When the vehicle input is 1,200 vph, the difference among the four control strategies are almost negligible in terms magnitudes, although EM, LM, and NEM can all reduce the average delay by at least 40%. At this input volume level, LM appears to perform the best and followed by NEM and EM. Except for the throughput improvements at the 1,200 vph input volume level, all improvements reported in Table 1 are

statistically significant at the 0.05 confidence level based on two sample t-tests.

The typical capacity for a two-lane highway with one lane closed is about 1,340 vph (Dudek, 1984). When the input volume increases to 1,600 vph (i.e., above the normal capacity), the differences are much more significant in terms of both percentage improvements and magnitudes. The NEM gives the best results for all performance measures, followed by LM and EM. Compared to EM and LM, the delay from NEM in this case is much smaller. The throughput generated by NEM is almost the same as the input, demonstrating its superior mobility performance. Not surprisingly, no control yields the worst results. The average throughput without any control is 1,343 vph, which is consistent with the capacity reported in (Dudek, 1984).

When the input volume increases from 1,600 vph to 2,000 vph, even the average delay for NEM goes up significantly. However, the trend observed under the 1,600 vph input volume level still holds. For EM and LM, the percentage improvements in terms of average delay and mean travel time decrease slightly compared to the 1,600 vph demand level, while the percentage improvements in terms of throughput stay approximately the same.

Overall, the results in Table 1 suggest that LM consistently performs better than EM under all flow conditions. Under oversaturated condition (e.g., 2,000 vph), the performance differences between EM and LM become marginal. On the other hand, NEM performs the best under both congested and oversaturated conditions. Although it also works better than no control under medium traffic (1,200 vph), it is slightly less effective than LM. This is probably because under such a condition, vehicles can relatively easily negotiate among themselves to find a suitable gap to merge.

Vehicle trajectory diagram

To illustrate how NEM adjusts the positions of individual vehicles and the benefits of doing so, the trajectories of vehicles in a randomly selected time frame

Table 1. Performance comparison of different control strategies.

Performance Measure	Merge Control Strategy			
	Base Case	Early Merge (EM)	Late Merge (LM)	NEM
		Volume Input 1,200 vph		
Average Delay (s)	9.6	5.5 (−42%)	2.6 (−73%)	5.5 (−42%)
Throughput (vph)	1199	1199 (0%)	1198 (0%)	1197 (0%)
Mean travel time (s)	119.1	115.0 (−3%)	112.1 (−6%)	114.2 (−4%)
		Volume Input 1,600 vph		
Average Delay (s)	274.8	121.9 (−55%)	64.8 (−76%)	9.7 (−97%)
Throughput (vph)	1343	1424 (6%)	1517 (13%)	1591 (18%)
Mean travel time (s)	384.3	231.4 (−40%)	174.3 (−55%)	118.5 (−69%)
		Volume Input 2,000 vph		
Average Delay (s)	561.6	374.6 (−33%)	372.5 (−34%)	80.9 (−86%)
Throughput (vph)	1341	1436 (7%)	1526 (14%)	1915 (43%)
Mean travel time (s)	671.1	484.0 (−28%)	482.0 (−28%)	189.8 (−72%)

Note: numbers in parenthesis are relative differences, which are calculated as (control case – base case)/(base case).

are plotted in Figure 7, in which green lines are trajectories of vehicles in the right closed lane and red lines are for vehicles in the left open lane. Under NEM control all green lines eventually turn red in the merging zone, meaning vehicles in the right (closed) lane are able to successfully merge into the left (open) lane before the lane closure point. While for no control, Figure 7 clearly shows that many vehicles in the closed lane have to wait for an extended period of time before they can merge into the open lane.

As shown in Figure 7, even when the input volume is relatively low (i.e., 1,200 vph), the impact of merging maneuvers on traffic flow is evident if no control is adopted. While NEM in this case can well handle the merging traffic and the resultant trajectories for vehicles in both lanes are clearly smoother than no control. There are no sudden decelerations for vehicles in both lanes, and vehicles in both lanes operate approximately at the speed limit. There are some overlaps among the green and red trajectories at the beginning of the metering zone, meaning there are vehicles in the open and closed lanes traveling side by side. As vehicles approach the merging zone, there are no overlaps among trajectories and vehicles are able to form high-density flow (not congested flow) with approximately equal distance headways.

As the input volume increases to 1,600 vph and 2,000 vph, the performance of no control deteriorates rapidly. On the other hand, NEM can still handle the traffic well when the input volume is just above the normal capacity, which is 1,340 vph (Dudek, 1984). Interestingly, Figure 7(e) shows that with a very high traffic input (i.e., 2,000 vph). A queue builds up at the beginning of the metering zone for NEM control, and the average speeds of both lanes drop significantly at this bottleneck. Beyond this bottleneck, vehicles in both lanes pick up speed quickly and eventually form high-density flow with approximately equal distance

headways at the merging point. Although this queue under NEM control is undesirable, the total delay caused by it is much shorter compared to the one generated by the no control counterpart.

Other than the mobility benefits of NEM clearly demonstrated in Figure 7, the trajectories show that NEM can help to reduce rear-end crash risk, by avoiding sudden decelerations and stop-and-go traffic. Additionally, the no control trajectories show that some drivers in the closed lane have to wait for an extended amount of time to be able to merge and may become increasingly impatient. This intuitively may contribute to aggressive and unsafe behaviors such as forced merge, and increase the risk of angle crashes.

Density

To further investigate how NEM performs, a VISSIM tool is developed to visualize how traffic density in the merging area changes over time and distance. The density maps for input volume = 1,200 vph under the NEM and LM strategies are presented in Figure 8(a), where the vertical axis is for time and the horizontal axis is for distance. A distance of 0 refers to the point 400 meters before the metering zone. Larger distance values are for locations downstream of the origin. Also, darker colors are for higher densities. Figure 8(a) shows no significant difference in terms of density distribution between NEM and LM under light traffic condition. This result is consistent with the mobility results in Table 1.

The density results for more congested cases (input volume = 1,600 vph and 2,000 vph) are presented in Figures 8(b, c), which clearly show that compared to LM the NEM control can better reduce and equalize the traffic densities of the open and closed lanes. Equal densities in both lanes can help to reduce lane changes (seeking higher speeds) and consequently

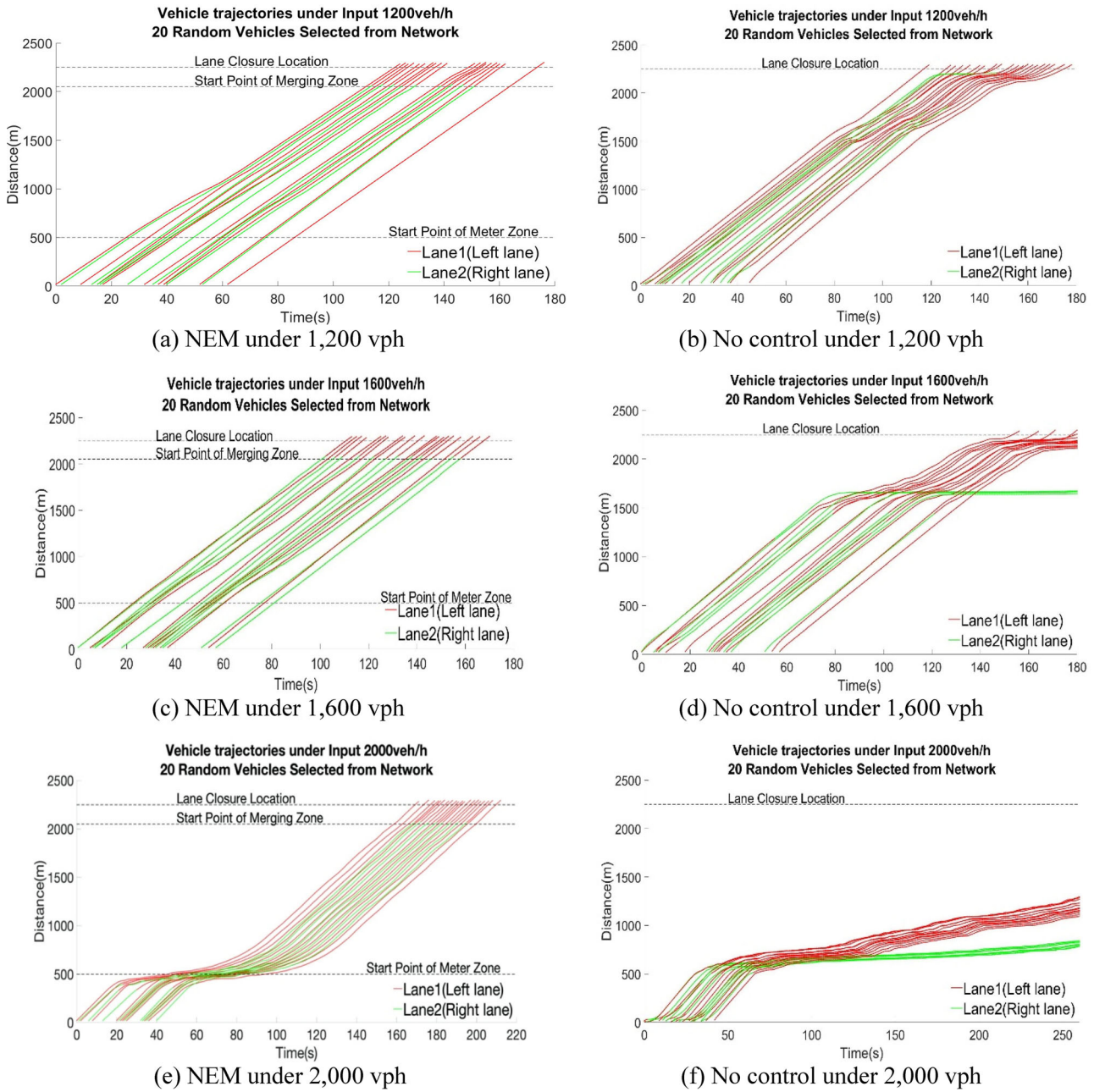


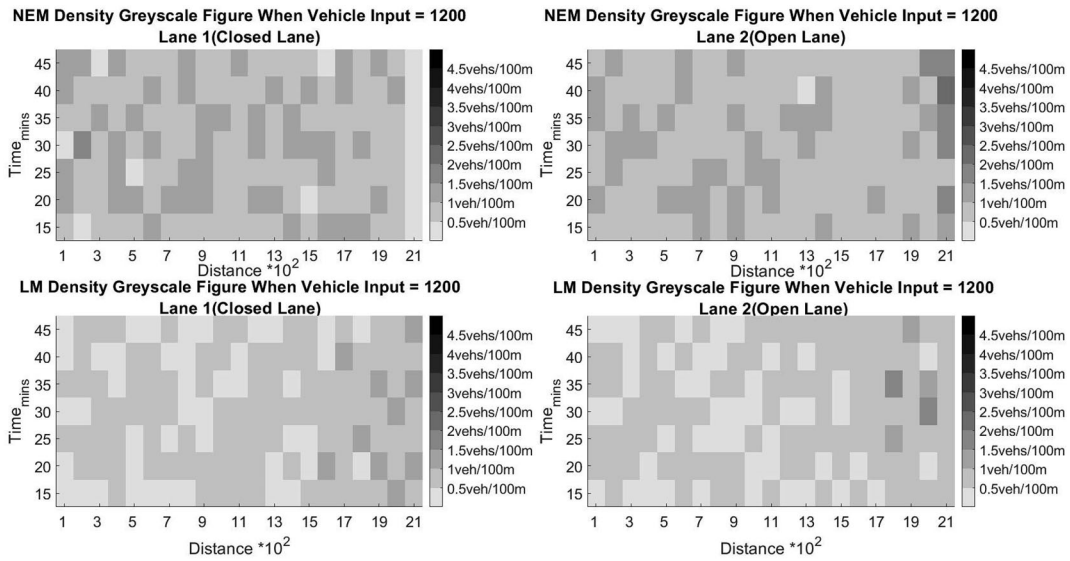
Figure 7. Vehicle trajectory diagrams.

angle crash risk. Additionally, a high-density area appears in Figure 8(c) at the beginning of the metering zone. This result is consistent with the trajectory diagram in Figure 7(e) and is caused by the mainline metering effect. Although generating a high-density area upstream of the metering zone is undesirable, the size of this area is much smaller than the one from the LM control (see Figure 8(c)). A smaller high-density area means the total vehicle time spent in stop-and-go traffic is less, suggesting that NEM is safer than LM particularly under congested conditions. Also, the density results in Figure 8(c) show that the queue from the NEM method grows at a much slower

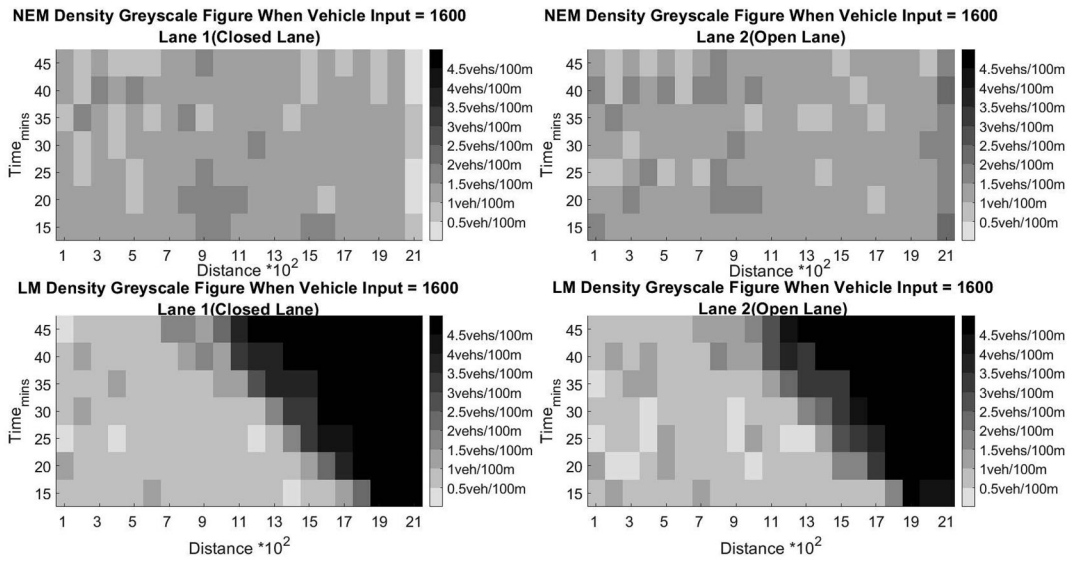
speed (i.e., backward forming shockwave speed) than the LM control. A slowly growing backward forming shockwave is likely to be less dangerous than a fast growing one. The environmental impacts of different merge control methods are not calculated in this research. However, from the results in this section, it is almost certain that NEM will result in less fuel consumption and traffic emissions.

Acceleration

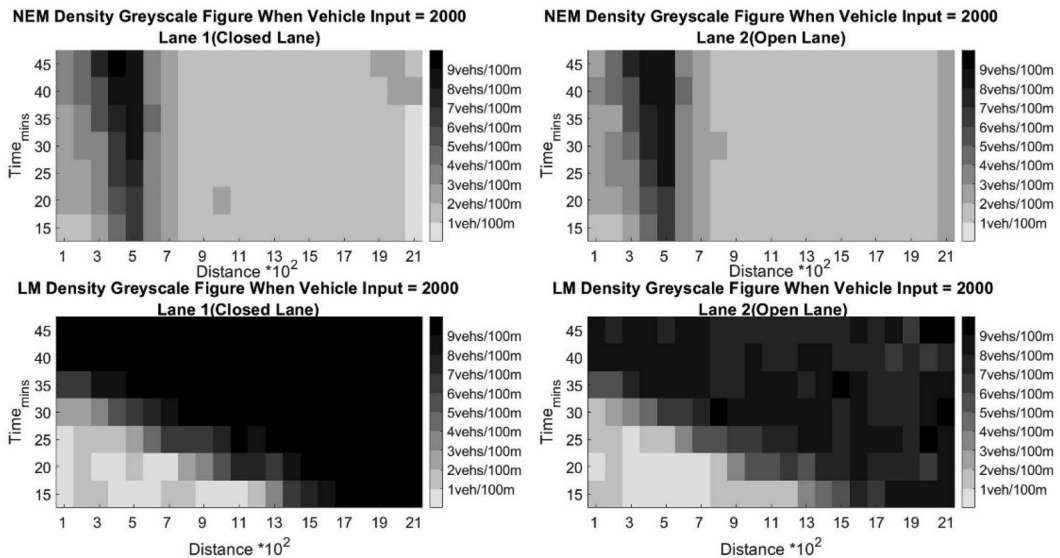
A majority of crashes in highway work zones are rear-end crashes, which are typically caused by sudden



(a) Volume = 1,200 vph



(b) Volume = 1,600 vph



(c) Volume = 2,000 vph

Figure 8. NEM and LM density map comparison.

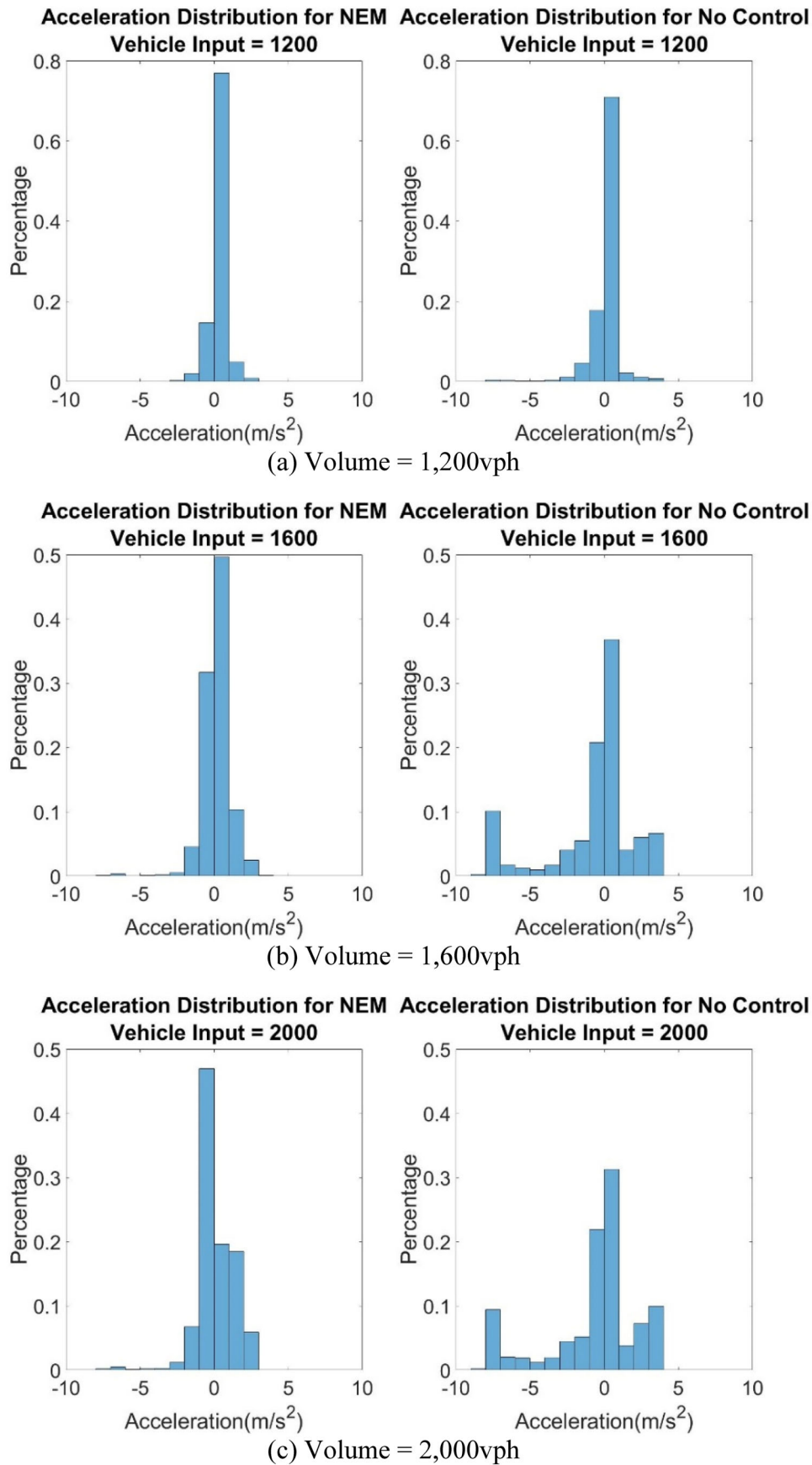
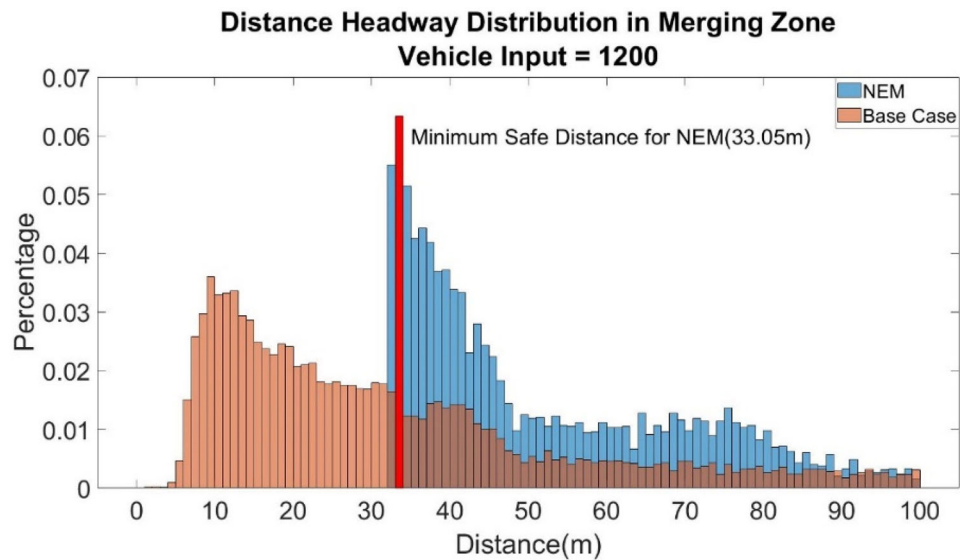
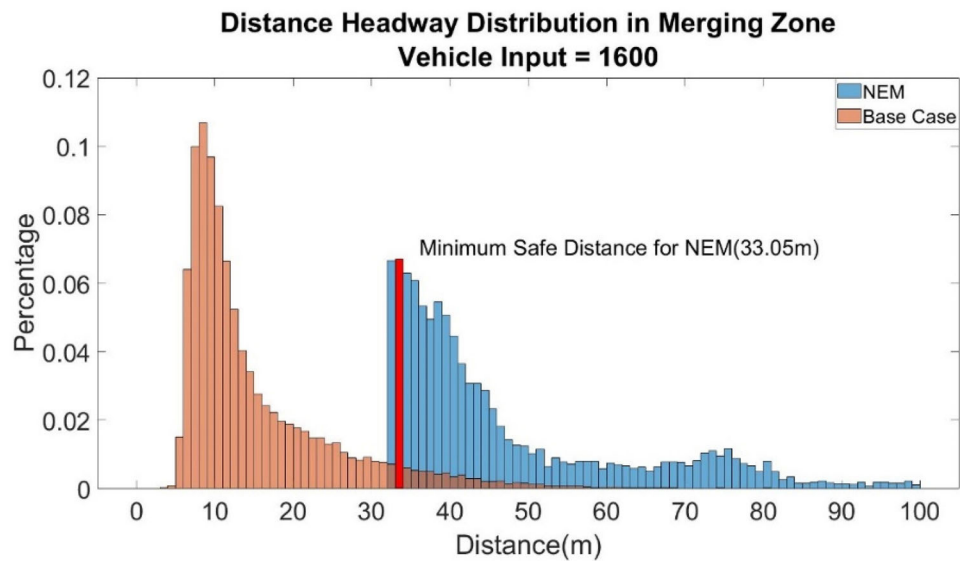


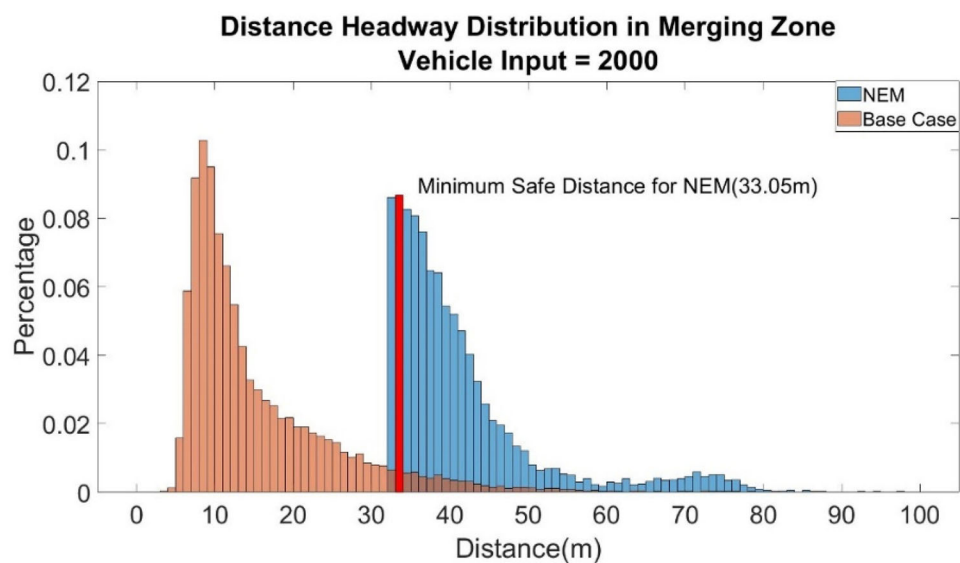
Figure 9. Acceleration histogram.



(a) Volume = 1,200 vph



(b) Volume = 1,600 vph



(c) Volume = 2,000 vph

Figure 10. Distance headway distribution in merging zone.

Table 2. Throughput results considering different car-following headways.

Time Headway (s)	Throughput (vph)			
	Base Case	Early Merge (EM)	Late Merge (LM)	NEM
Volume Input 1,200 vph				
1.2	1190	1199	1197	1196
1.5	1196	1198	1196	1196
1.6	1199	1199	1197	1196
1.7	1199	1199	1198	1197
1.8	1186	1199	1198	1193
1.9	1181	1198	1197	1188
2.0	1179	1198	1196	1186
Volume Input 1,600 vph				
1.2	1359	1523	1523	1593
1.5	1399	1514	1526	1592
1.6	1365	1478	1515	1592
1.7	1343	1424	1517	1591
1.8	1335	1412	1515	1565
1.9	1296	1403	1511	1542
2.0	1331	1398	1512	1529
Volume Input 2,000 vph				
1.2	1371	1338	1536	1876
1.5	1430	1457	1532	1912
1.6	1425	1442	1519	1913
1.7	1341	1436	1526	1915
1.8	1329	1428	1523	1861
1.9	1321	1419	1519	1774
2.0	1312	1411	1516	1725

decelerations and stop-and-go traffic. Therefore, the stability of vehicle longitudinal acceleration behavior can be an important surrogate safety measure. Figure 9 shows the longitudinal acceleration distributions of vehicles under NEM and no control. For relatively low input traffic volumes such as 1,200 vph, the acceleration distributions for NEM and no control are similar, with the NEM distribution to be slightly more centered around 0. As the input volume increases to 1,600 vph and 2,000 vph, the acceleration distributions for no control clearly are more spread out than those for NEM, and NEM generate much less sudden decelerations (e.g., $\leq -5 \text{ m}^2/\text{s}$). This suggests that NEM is much safer than no control and leads to smoother and more stable traffic flow.

Distance headway

Figure 10 shows the distance headway distributions for NEM and no control. Under all input flow conditions, NEM results in larger (safer) distance headways in the merging zone than no control. With NEM control, the generated minimum distance headway is around 33 meters. Given the posted speed limit of 70 km/h, this minimum distance headway is equivalent to 1.7 seconds, which is the desired headway time (CC1) between the lead and following vehicles used in the Wiedemann 99 car-following model. This shows that NEM results in orderly merge maneuvers in the merging zone. Also, this implies that vehicles do not

Table 3. Average delay results considering different car-following headways.

Time Headway (s)	Average Delay (s)			
	Base Case	Early Merge (EM)	Late Merge (LM)	NEM
Volume Input 1,200 vph				
1.2	9.6	6.7	2.4	5.3
1.5	7.7	6.0	2.6	5.4
1.6	8.2	5.8	2.6	5.5
1.7	9.6	5.5	2.6	5.5
1.8	12.5	5.7	2.5	5.9
1.9	19.4	5.8	2.6	7.6
2.0	24.0	5.9	2.6	8.2
Volume Input 1,600 vph				
1.2	233.4	83.5	57.3	9.5
1.5	213.2	92.2	60.7	9.5
1.6	223.5	110.3	62.6	9.7
1.7	274.8	121.9	64.8	9.7
1.8	278.4	128.6	67.1	11.5
1.9	283.1	139.5	72.9	19.6
2.0	281.7	149.1	72.7	39.5
Volume Input 2,000 vph				
1.2	526.5	432.2	348.9	99.4
1.5	476.8	342.7	366.3	82.5
1.6	523.2	359.5	370.1	81.8
1.7	561.6	374.6	372.5	80.9
1.8	573.9	384.2	373.4	101.3
1.9	588.2	402.1	374.1	132.5
2.0	596.8	410.6	374.4	154.8

need to adjust their speeds much after merging into the open lane, which is beneficial to improve work zone safety.

Sensitivity analysis

Since the proposed New England Merge (NEM) requires vehicle longitudinal control to be automated, time headway in VISSIM car-following model is a critical parameter. For the above simulation analysis, the time headway parameter is set to 1.7 s as recommended by Yang et al. (2009). To further assess the impacts of this parameter on the modeling results, a range of time headway values (1.2 s~2.0 s) is considered and simulated using VISSIM. This generates 84 scenarios and 1,680 simulation runs are conducted. The results are provided in Tables 2 and 3 and are also discussed below.

As the time headway parameter increases from 1.2 s to 2.0 s, in general the performance of all control methods degrades consistently. The reductions in performance are more significant for the proposed NEM than other control methods, particularly when the input volume is at the 1,600 vph and 2,000 vph levels. These results suggest that human drivers are less sensitive to relatively small changes in headway. A potential explanation is that such variations (1.2 s~2.0 s) are insignificant compared to perception and reaction time. The perception and reaction time and the impreciseness of human driver control both

contribute to diminishing the impacts of the above time headway variations.

While for automated vehicles, their longitudinal controls are very precise and they follow the time headway strictly. These make them more sensitive to changes in time headway. However, one thing worth noting is that the worst performance of NEM is still clearly better than the best performance of other methods at the 1,600 vph and 2,000 vph input levels.

When the input volume is at 1,200 vph, the theoretical average headway is 3.0 s. The VISSIM simulation results show that varying time headway in this scenario has more significant impacts on the Base Case (no control) and NEM control than Early Merge (EM) and Late Merge (LM). Overall, the changes here are much smaller compared to those under the 1,600 vph and 2,000 vph input volumes. This suggests that NEM needs to be further improved for low to medium traffic. This is consistent with the results in Table 1. At the 1,200 vph input level, the mechanism for varying time headway (i.e., from 1.2 s to 2.0 s) to affect traffic operations might be different from those at 1,600 vph and 2,000 vph. NEM is probably too restrictive for an input of 1,200 vph. For example, vehicles in the open lane have to increase their headways even when there are no merging vehicles in the closed lane.

In summary, the results show that NEM performs well over a range of time headways, not just a single value. Increasing time headway does cause NEM performance to degrade. However, it still clearly outperforms other methods considered in this research, particularly for heavy traffic.

Conclusions and discussion

This study proposes a novel highway work zone cooperative merge control strategy termed New England Merge (NEM), which is evaluated using microscopic traffic simulation and compared with no control, late merge, and early merge based on safety and mobility measures. It is found that NEM generates significantly higher throughputs and lower delays and average travel times than all other control methods under congested traffic conditions, and comparable mobility performance with late and early merges under light traffic conditions. In addition to delay, travel time, and throughput, sample trajectories from NEM and LM are plotted. The results clearly illustrate the mobility as well as safety advantages of using NEM under various traffic input conditions compared to no control. The trajectory diagrams show that

NEM can generate high-density flow with approximately equal distance headways in the merging zone and reduce sudden decelerations and stop-and-go traffic, contributing to improved mobility and safety for highway work zones. The results suggest that it is important and beneficial to consider cooperative driving to improve traffic operations at highway work zones. This raises an interesting question about whether it is ethical to mandate all vehicles to behave cooperatively. Also, how can we further improve the cooperative rules to make the merging process both highly efficient and ethical. These topics are beyond the scope of this paper and will be addressed in our future research.

A tool is developed in this research to visualize the spatial and temporal distributions of traffic density as a result of adopting NEM and LM control strategies. The density maps show that NEM can help to equalize the traffic densities in the open and closed lanes, reduce the chance for congested flow (i.e., stop-and-go traffic), and avoid fast-growing long queues. All these contribute to improving work zone mobility and safety. The distributions of longitudinal accelerations and distance headways for NEM and no control are also presented. The results indicate that NEM generates smoother traffic flow and much less sudden decelerations than no control, contributing to improved work zone safety.

Similar to late merge and early merge, implementing this NEM in practice would benefit from careful planning and proper law enforcements, such as setting up dynamic message signs and automated photo enforcement. With the developments in connected and automated vehicle technologies, the NEM will become increasingly applicable. In fact, some vehicles today are already equipped with the *adaptive cruise control with stop-and-go* technology, which automates vehicle longitudinal control and allows drivers to specify the desired speed and distance headway. Such a technology is ideally suited for NEM control. Technically, it is not difficult to add vehicle-to-infrastructure (V2I) capability to these vehicles so that they can receive NEM control instructions from road-side units associate with work zones.

Overall, the analysis results show that NEM is a promising merge control strategy for highway work zones. It proposes to address work zone mobility and safety from an unconventional perspective (i.e., longitudinal control). As a first attempt along this direction, there is certainly room for improvements. In future research, the proposed longitudinal control algorithms for Metering Zones I and II can be further

improved. For example, the fixed $CC1_{open}$ parameter may be replaced by a traffic flow dependent variable, and more sophisticated models may be formulated to determine the optimal accelerations in Metering Zone II. The lengths of Metering Zones I and II are static and determined empirically in this research. Such a restriction can be relaxed to develop a dynamic version of NEM. For multi-lane (≥ 3) highways or freeway on-ramps (Jin et al., 2017), the proposed NEM cannot be directly applied and this can be another interesting research direction. Additionally, more sophisticated surrogate safety measures (Arvin et al., 2019; Huang et al., 2013; Wang et al., 2018; Wang & Stamatiadis, 2014, 2016; Wu et al., 2019) can be considered to quantify the safety benefits of NEM.

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