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Gap metering for active traffic control at freeway merging sections

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ABSTRACT

Freeway merging sections are critical segments that can recurrently activate peak-hour traffic congestion. This article proposes a novel vehicular gap control method as a new Active Traffic Management (ATM) strategy to be added to the existing Intelligent Transportation System (ITS) toolboxes for freeway merge control. The proposed strategy, "Gap Metering," can be considered a non-stopping mainline version of ramp metering. It utilizes signals advising mainline through vehicles to yield sufficient gaps for merging vehicles. Detailed system design and control methods are proposed and implemented in VISSIM (please spell out the abbreviation of VISSIM for this first instance), a microsimulation software package. Different driver behavior sets with different standstill headway values are created to allow switching between gap-metered vehicles and regular vehicles. We evaluate the proposed system through two VISSIM models built and calibrated, respectively, for both the I-894 corridor in Milwaukee, WI, and the Riverside Drive segment on I-35 northbound in Austin, TX. Both corridors experience severe morning peak-hour congestion. We use the I-894 corridor for testing the system design parameters and use the I-35 corridor to conduct a comparison with the ramp metering strategies. The I-894 results indicate an average of 10–20% network delay reduction among all scenarios. We then tested the scenario on the I-35 corridor and compared with the ALINEAR ramp metering. Gap metering strategies alone or combined with ramp metering can, respectively, reduce 17% and 27% more total delay than ramp metering only control at 20% compliance rate.

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active traffic management; gap metering; merging control; ramp control; ramp metering

Introduction

Traffic congestion caused by bottlenecks contributes about 40% of the total urban congestion (Lomax & Schrank, 2005). On freeways, the activation of recurrent bottlenecks has a close relationship with geometric changes, such as merging and diverging, weaving sections, and lane drops. A key traffic characteristic of such bottleneck locations is the high "merging" demand observed when drivers seek appropriate lanes to execute their route selections. However, a driver's desire to minimize his or her own travel times can cause traffic flow to become denser (with fewer gaps) as traffic volume increases. Such conflicts between the merging demand and the supply of gaps for merging during high volume conditions can result in significant mobility (such as traffic breakdown and stop-and-go waves) and safety (e.g., rear-end and side-swiping crashes) consequences. This article focuses on proposing a new Intelligent Transportation System (ITS) technologies for Active Traffic Management (ATM) (Fang & Jin, 2015) at merge sections.

In the past, ATM strategies such as ramp metering and variable speed limits have been widely deployed in order to smooth traffic flow along these sections by controlling the speed and flow. Ramp metering improves the merging efficiency by smoothing and restricting excessive ramp demand (Kotsialos, Papageorgiou, & Middelham, 2005; Jacobson, Stribiak, Nelson, & Sallman, 2006). Variable speed limits warn travelers of downstream congestion to allow smoother approaching congested segments (Borrough, 1997; Papageorgiou, Kosmatopoulos, & Papamichail, 2008; Hassan, Abdel-Aty, Choi, & Algadhi, 2012; Soriguera, Torné, & Rosas 2012; Carlson, Papamichail, & Papageorgiou, 2012; Kattan, Khondaker, Derushkina, & Poosarla, 2015; Lin, Kang, & Chang, 2015; Kianfar, Edara, & Sun 2015). However, to effectively improve the merging efficiency at those sections, the key control variable is in fact the density or vehicle gaps. Researchers have been exploring control frameworks (Hou, Xu, & Yan, 2008) using traffic density as the targeted control variable, which is indirectly controlled

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Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/gits.

by variable speed limit and ramp metering. Meanwhile, in work zone operations, engineers have also explored dynamic merge control technologies to temporarily adjust the gap distribution near work zones to improve the merging safety and efficiency (Datta, Schattler, Kar, & Guha, 2004; Harb, Radwan, Abdel-Aty, & Su, 2011; Rayaprolu, Ishak, Qi, & Wolshon 2013). Representative work zone merging control strategies include early, late, and dynamic merging. For early and late margining, guidance signs and signal controls are deployed to promote merging at the earliest or the latest point when vehicles enter the merging section. In dynamic merging, the control modes switch between early merge, late merge, and no control based on prevailing traffic conditions. Researchers and engineers have examined implementing a "dynamic" version of such strategies on normal sections with recurrent bottlenecks. However, the complicated control system design and the need to switch between several controlling modes make it difficult to implement as a control signal system for daily operations.

In this study, a simple gap metering (GM) system is proposed for directly adjusting the gap distribution of the mainline traffic flow. The system advises drivers on mainline through lanes to yield gaps before entering a merging area. The detailed system design, control logic, and control devices are discussed. To evaluate the effectiveness of the proposed system, the system is simulated using the VISSIM API (Application Programming Interface). A baseline VISSIM model is calibrated using 5-min traffic counts for both the freeway and arterial network of the I-35 northbound/Riverside Drive segment in Austin, TX. The impact of control strategies and compliance rate are explored by comparing the performance changes between the baseline and the simulated control scenarios.

Existing active merging traffic control technologies

Ramp metering and its mainline variations

Ramp metering is an ATM strategy that emerged in the 1990s (Datta et al., 2004). It uses metering signals to smooth and control vehicular flow on ramps. The key benefits of ramp metering include the ability to reduce the disturbance that ramp flow incurs on the mainline, and to balance the ramp demand with mainline capacity (Jacobson et al., 2006). Successful deployment of ramp metering systems can be found in many locations within the United States (Gordon & Trombly, 2011), including Minneapolis (MN), Seattle (WA), Denver (CO), Long Island (NY), and Portland (OR). System components include the signal and warning signs, detecting system, controllers, and communications. Ramp metering systems have been reported to produce significant safety and mobility improvement, with a 15–25% collision reduction and a 9%-25% increase of average speed (Jacobson et al., 2006).

Direct migration of ramp metering onto the mainline can cause overwhelming stopping delay and essentially violates the mobility concept of freeway; therefore, the concept was only field tested at toll plaza, bridges, and tunnels (Piotrowicz & Robinson, 1995). However, even with those special locations, very limited success has been achieved, and most of those meters were eventually discontinued. Dynamic merging lane closure, a more effective mainline variation of ramp metering, applies lane control signals to close the rightmost lane on the mainline upstream of an on-ramp to allow ramp traffic to merge without interacting with mainline traffic flow. Representative implementation can be found in Germany and the Netherlands (Hellernan, 2010). The system includes a lane control signal installed on an overhead gantry. When ramp traffic flow increases to a predefined threshold level, the lane control algorithm will display signs to indicate "lane closed." A significant reduction of total VHT (vehicle hours traveled) is reported with significant improvement for ramp flow. This control method separates mainline traffic from ramp traffic upstream of the merging area at the cost of temporarily reducing the mainline capacity by one lane. This may create a new bottleneck for the upstream traffic flow and cause even more congestion problems on already crowded corridors.

Dynamic merge control at work zones

To reduce safety and mobility issues at the merging points of work zones, several merge control strategies have been introduced and implemented in the past including the early merge, late merge, dynamic merge, dynamic lane control, and lane-based signal merge.

Early Merge (EM) control encourages drivers to merge into the continuing lane(s) near a specific point located well in advance of the lane closing. Early merge control can be effectively implemented under light traffic conditions when drivers in the closing lane can find gaps relatively easily to merge with traffic in the open lane. When demand exceeds capacity, however, queues may grow beyond the initial lane closure sign, increasing the risk of rear-end collisions (Pesti et al., 2008). Indiana DOT has tested an innovative method for providing early merge information via dynamic message signs. When a queue is detected, a signal is sent causing the upstream sign to flash and alert drivers not to pass. In 2001, Tarko and Venugopal (2001) studied the Indiana system and found capacity to decrease by 5% when it was in place. The authors hypothesize that the effect is due to driver unfamiliarity with the new system—an effect, which should diminish as the new system becomes more widespread. As part of the same study, statistical models were used to predict the impact of the Indiana early merge system and found it to have a 40% reduction in merging conflicts and a 39% reduction in braking conflicts. Michigan DOT has implemented a similar dynamic early merge system on freeways where two lanes are reduced to one lane and has found a three-lane to two-lane reduction to also work well under this system (Datta et al., 2004).

A *Late Merge (LM)* strategy is one that directs drivers to stay in their lane until the specified merge point, where drivers in each lane will take turns proceeding. Pesti, Jessen, Byrd, and McCoy (1999) evaluated PennDOT's implementation of late merging, finding it more effective than conventional merging when the freeway is congested. The late merging strategy was also found to lead to higher capacity and fewer traffic conflicts. Beacher, Fontaine, and Garber (2005a, b) did a similar evaluation for Virginia DOT, but the results were less compelling. The volume split between lanes was more even than under conventional merging, but the changes to other performance metrics such as throughput time and time in queue were not statistically significant. The authors hypothesize that other variables may be influencing the results such as characteristics of the driver population, vehicle mix, or site-specific characteristics. In a simulation study, the same authors (Beacher et al., 2005a, b) concluded that late merge may only be helpful when heavy vehicles are at least 20% of the traffic stream.

Dynamic Merge (DM) strategy is an adaptive strategy that switches between different merge control modes based on the prevailing traffic conditions. Pesti et al. (2008) concluded that late merging is effective during the peak periods but may be dangerous during high-speed off-peak conditions. For this reason, Pesti and McCoy (2001) developed the dynamic late merge strategy where changeable message signs dictate when congestion is sufficient for late merging to be implemented. Kang, Chang, & Paracha (2006) evaluated dynamic late merging in Maryland, finding higher throughput, more equal lane volume distribution, and lower maximum queue length when compared to the conventional merging condition. The authors suggest that more research is needed to determine when dynamic lane merging should be activated and to assess drivers' learning curves. Pesti et al. (1999) used microsimulation to evaluate dynamic late merging under a variety of conditions and found it to work well when the lane closure plan is two to one, four to one, and four to two. Grillo, Datta, and Hartner (2008) evaluated the dynamic late merging system in Michigan, finding improved flow and an increased percentage of vehicles that merged at or near the taper location when compared to conventional merging conditions. Meyer (2004) used real-time traffic monitoring to test the use of changeable message signs to switch between early merging, late merging, and incident mode during construction along a Kansas highway. An on-ramp near the merge area may have led to the limited positive impact found by late merging, as drivers change to the left lane to allow incoming drivers to enter the highway.

Lane-based Signal Merge (LBSM) is an alternative to directing drivers to take turns at the merge point using traffic signals. Signals can be used for fixed cycle merge metering or continuous merge metering, where red and green phases are alternated similar to a ramp meter with the goal of keeping flow moving. Testing of signalized lane control at work zones has, to date, been limited to simulation. Lentzakis, Spiliopoulou, Papamichail, Papageorgiou, and Wang (2008) tested various control schemes for when the signals should be turned on, given a three to one lane configuration and two cars per green phase policy. The study found occupancy rates of greater than 5% to work better than no-control on average. Yang, Chang, and Kang (2009) found via microsimulation that signal control is preferable to alternate strategies when volume exceeds 800 vphpl. Wei, Pavithran, Yi, Yang, and Zeng (2010) evaluated two to one, three to one, and three to two lane closure scenarios in a microsimulation model and found volume thresholds at which the two types of signal control perform better than late merging. The volume thresholds, however, do not consider inevitable diversion to alternate routes. The importance of this point will be considered further in the next subsection.

Merging conflicts

The key issue in merging, weaving, and diverging section is the lack of sufficient gaps in the through traffic that can be used by merging vehicles. As pointed out by Wu and Tian (2005), the capacity of a merging area is highly related to the mainline gap distribution. However, due to the nature of traffic flow, as congestion increases, the available gap on mainline will decrease due to the reduced average spacing. Notwithstanding, some driver behaviors may also alleviate the merging conflicts. Drivers may seek to merge before reaching the merging areas to the mainline, and courteous drivers may yield a gap for merging and weaving vehicles. While such volunteer actions may help reduce the merging conflicts, they can also cause problems when interacting with drivers who are not willing to or do not expect others to conduct such actions.

Proposed gap metering system design

Conceptual design

In this study, we present a new concept of ATM by exploring the methods of directly controlling traffic gaps and

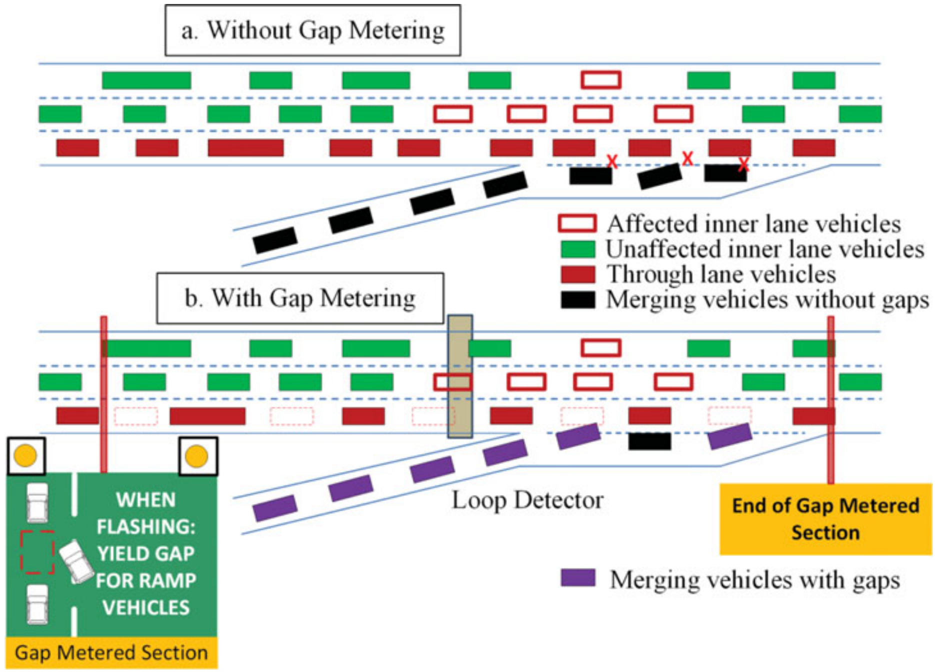


Figure 1. Conceptual diagram for the proposed gap metering system.

spacing on the mainline without effectively stopping the traffic flow or switching between different control strategies. At a typical freeway on-ramp section, the main merging conflicts are between the ramp vehicles (the black blocks in Figure 1) and the mainline vehicles on the through lane. Meanwhile, vehicles on the inner lanes can still be affected when through-lane vehicles attempt to make lane changes to avoid conflicts or when ramp vehicles make subsequent lane changes after merging onto the mainline. Such merging conflicts can create "frictions" or temporary microscopic bottlenecks that trigger large-scale recurrent bottleneck congestion. Meanwhile, some courteous drivers may help alleviate such merging conflicts by yielding a large gap temporarily for a ramp vehicle to merge in the front. However, such courteous maneuvers may also cause shock waves or oscillations upstream as vehicles need to slow down or even stop to create the large gaps. The proposed idea is to use traffic signs to guide or regulate mainline through-lane vehicles to yield gaps before entering merging areas as illustrated in Figure 1b. Ramp vehicles can then move into the created gaps (in the figure's dashed blocks) with minimal effort or courtesy stopping/slowing down by the lane vehicles. A proposed design for a GM sign is found in the bottom left of Figure 1. The sign contains a picture explaining the suggested maneuvers, and two flashing beacons indicate whether the GM is activated.

As Figure 2 shows, the proposed GM system includes three sections. The first section is a *warning section*. Warning signs are installed to notify the mainline drivers of gap-controlled sections downstream. At the *enforcement section*, the proposed GM signs are displayed to guide

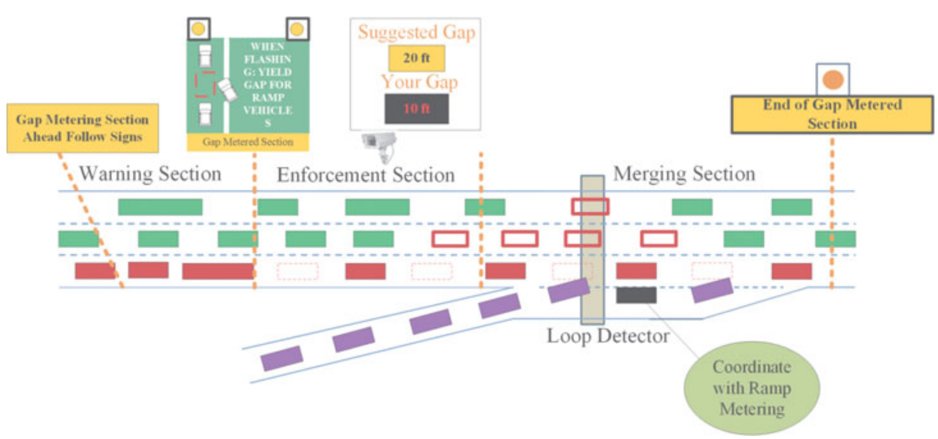


Figure 2. Advanced gap metering system design.

drivers to yield a gap. To promote compliance, reflective gap signs (similar to reflective speed limit signs) may be installed with video or radar sensors to determine vehicle spacing. At the *merging section*, mainline vehicles maintain their gaps until filled by a ramp vehicle. Flashing beacon and traffic signs can be used to indicate the end of the gap metered section. Meanwhile, traffic detectors such as inductive loop or remote traffic microwave sensor (RTMS, in gray box across all lanes in Figure 1b) may be installed at the merging section. The detected traffic occupancy can be used to determine the activation of the GM system through an on-site communication and controller system. Furthermore, the coordination with ramp metering may be necessary to improve the merging efficiency. When ramp metering is not available, similar signs can guide ramp vehicles to keep enough spacing for smooth merging. Implementation of the GM system needs to consider the following key design parameters.

- *Lanes metered*: GM systems can be implemented either for only the rightmost general-purpose lane or for the entire approach. For the latter case, the DMS or control signals are attached to an overhead gantry to control the metered lanes. In more advanced control scenarios, for implementation over an entire approach, GM for each lane may be activated at different congestion levels to reduce the disturbance to the inner general purpose lanes.
- *Gap size*: The size of the gap to be yielded is also an important factor. The system relies on the driver's interpretation of the required spacing for one vehicle to merge in the front. Other scenarios such as time headway- or spacing headway-based method can be implemented using feedback gap signs similar to the feedback speed limit signs if effective gap detectors are used. When using spacing, different spacing requirements may be needed for different speed differences prior to merging. If the merging vehicles can synchronize their speed with the mainline traffic, a uniform spacing can be used. However, when merging vehicles are queued at the merging point and the mainline traffic flow is still in high speed, the gap size may need to be higher to facilitate those merging vehicles in queue to join the mainline traffic flow.
- *Yielding strategy*: Yielding strategy for mainline through vehicles is another design factor to be considered. After allowing one vehicle at the front, the mainline through vehicle can choose to keep the one-vehicle spacing or just closely following the preceding vehicle as in normal traffic flow. Different yielding strategies may result in different version of messages to be displayed. For example, as illustrated in Figure 2, to keep the spacing, we can use "KEEP ONE VEH GAP" (KOV) on the DMS; while to allow vehicles to convert back to normal, we can use "ALLOW ONE VEH IN FRONT" (AOV).
- *Compliance rate*: Compliance rate is a critical factor on the effectiveness of the proposed system. The system needs to be evaluated for various levels of compliance rates to determine the optimal control strategy. High compliance rates may be achieved by providing feedback gap signs that display the required gap and the detected gap of an approaching vehicle, similar to feedback speed limit signs. Law enforcement may also be needed to promote the compliance rate. Meanwhile, the system may also work well in medium or low compliance rate. If so, the driver feedback component can be implemented as warning signs. Some design factors may also affect compliance rate, e.g., drivers from inner general purpose lanes may be less compliant than those on rightmost general purpose lane. Yielding larger gaps, e.g., two-vehicle gap, may be unacceptable for many drivers.

Control framework

The control framework of GM system is illustrated in Figure 3. The GM system relies on the inputs from bottleneck identification to provide candidate locations to deploy the system. When other Active Traffic and Demand Management (ATDM) strategies have been implemented on the same corridor at the Traffic Management Center (TMC), additional investigation may be required to evaluate the interactions between GM and the existing control strategies. The key components of the GM system are within the dashed block in Figure 3, in which the controller interacts with existing traffic management systems at TMCs. GM uses DMS or signals to interact with mainline metered traffic and to interact with ramp traffic and unmetered mainline traffic indirectly. Feedback can be provided through traffic detectors. GM can be activated either by traffic occupancy exceeding a predefined threshold or by the start of peak hours.

Experimental design

We design the simulation studies in two steps. The first step is to conduct a comprehensive study on the system parameters and identify optimal control strategies based on the simulation results of the I-894 corridor. At the second step, we compare GM with ramp metering based on the I-35 corridor data. VISSIM models were calibrated to replicate the actual conditions on both corridors. I-894 corridor starts from S. 84th Street and ends at W. Greenfield Avenue. There are eight major interchanges along

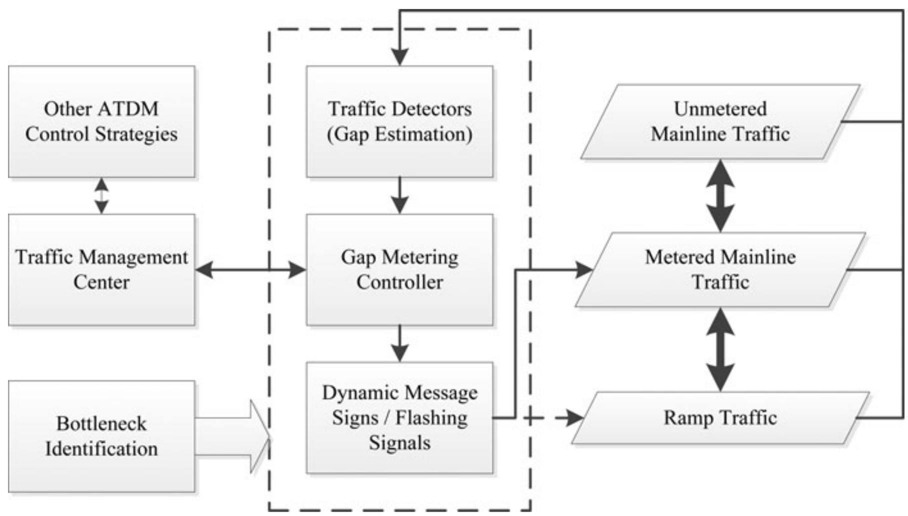


Figure 3. Gap metering control framework.

this four-mile segment. Five-minute loop detector data were used to calibrate the baseline model. A mean percentage error of speed is achieved within 10% during the calibration. The simulated time period is between 5:30 and 9:30 AM, during which two recurrent bottlenecks become active from 7:30 to 9:00 AM. The GM system is only deployed at two locations at the Northbound direction of the on-ramps at National Avenue and Beloit Rd according to a previous bottleneck identification study for this corridor (Jin, Parker, Fang, Ran, & Walton, 2012). The I-35 NB riverside corridor is between the Highway 71 and Riverside Drive. There are four major interchanges with two weaving sections and one entrance ramp only location. The simulation model is established and calibrated based on field data collected during the morning peak hours (7:00–9:00 AM) at the I-35 Northbound/Riverside Drive segment in Austin, Texas on April 11, 2012. The corridor suffers significant peak-hour congestion due to the combination of horizontal and vertical curves at Riverside Drive and heavy commuting and freight traffic. Figure 4 shows a satellite view of the segment. Twelve video cameras are installed on two overpass bridges and at three intersection locations to record vehicle movements on both freeway and frontage roads. The video data are then processed into traffic counts as inputs for VISSIM.

The driver behavior under GM is achieved by adjusting the standstill distance (CC0) in Wiedenmann 1999 car-following model, which controls the minimal spacing (22). An additional value of 20-ft (6.10 m) equivalent to one-vehicle spacing is added to the calibrated CC0 value in order to simulate the yielding of one-vehicle gap. This increases the CC0 value from its calibrated value 4.28 ft (1.30 m) to 24.28 ft (7.40 m). It should be noted that CC0 provides a lower bound for the spacing, and VISSIM Wiedenmann 1999 model will provide the variations of spacing caused by the perception-reaction process in car-following behavior. During free-flow condition in VISSIM, the GM vehicles do yield larger gap and when synchronized can be utilized right away by ramp vehicles. During traffic congestion, the GM vehicles operate with spacing close to the assigned CC0 values. Nevertheless, the value of CC0 is not designed for heavy vehicles which only consists a small fraction of vehicles in the simulated network. VISSIM COM (Component Object Model) Application Programming Interface (API) is used to implement the detailed control scenarios. Several scenarios of each key design factors are considered. For lanes metered, the simulation evaluated one-right-lane, two-right-lane, and full-approach implementation. For yielding strategy, both AOV and KOV are applied. The KOV is simulated by keeping the extended spacing all the time for gap metered vehicles at merge sections; while AOV is implemented by allowing CC0 to switch back to the original 4.38 ft (1.3 m) after one ramp vehicle merged in front of the gap metered vehicle.

The driver behavior in both one-lane and two-lane GM scenarios is based on the calibrated VISSIM model. Car-following and lane-changing behavior remain the same except for the additional CC0 gaps. When gap metered vehicles open up gap, it does attract both ramp and mainline vehicles to take those gaps. The COM model did not restrict any of those mainline vehicle lane-changes or car-following behaviors.

The activation of GM is between 7 and 9 AM. Finally, the compliance rate is evaluated at 10%, 30%, 50%, 80%, and 100%. Each control scenario is run against five different random seeds. To reduce the number of simulation runs, the experiment conducted full enumeration of design factor variations for lane-implemented, yielding strategy, and compliance rate; then, the best scenario is tested for different congestion activation scenarios.

(a)

(b)

Figure 4. Experimental sites (a) I-894 NB Corridor, Milwaukee, WI USA (b) I-35 NB, Austin, TX, USA.

Results and discussion

I-894 system design factor evaluation

The effectiveness of GM is evaluated using average vehicle delay, total throughput, and total vehicle hours traveled (VHT) of the entire corridor, although the recurrent bottleneck is only located at the NB segment of this corridor. The purpose is to evaluate if the congestion has been pushed upstream, thereby not resulting in overall improvement of corridor traffic condition. Table 1 lists the relative reduction in average vehicle delay of the tested scenarios with respect to the baseline condition. All listed numbers are average numbers from five different random seeds. It is found that combined implementation of GM rules on both the mainline and the ramp can significantly improve the traffic conditions at the merging area compared with mainline only implementation. Meanwhile, the improvement from one-lane to two-lane implementation is significant, while the change from two-lane to three-lane implementation is not. This indicates that the vehicles merging at the study sites have a minor impact on the leftmost lane. In general, AOV yielding strategy has superior performance to KOV. Moreover, a compliance rate increase does not always result in positive effects on GM. One phenomenon that stands out is that when only mainline drivers fully comply with GM, traffic conditions may become worse. In this scenario, merging vehicles do not effectively use the gaps created by vehicles on the mainline, thereby causing a significant capacity drop that outweighs the congestion reduction impact of GM. The best performance is achieved when metering the gap on the two rightmost generation purpose lanes and the ramp based on the AOV strategy. The aforementioned results illustrate the promising potentials of GM system to be used as a new, effective ATDM strategy.

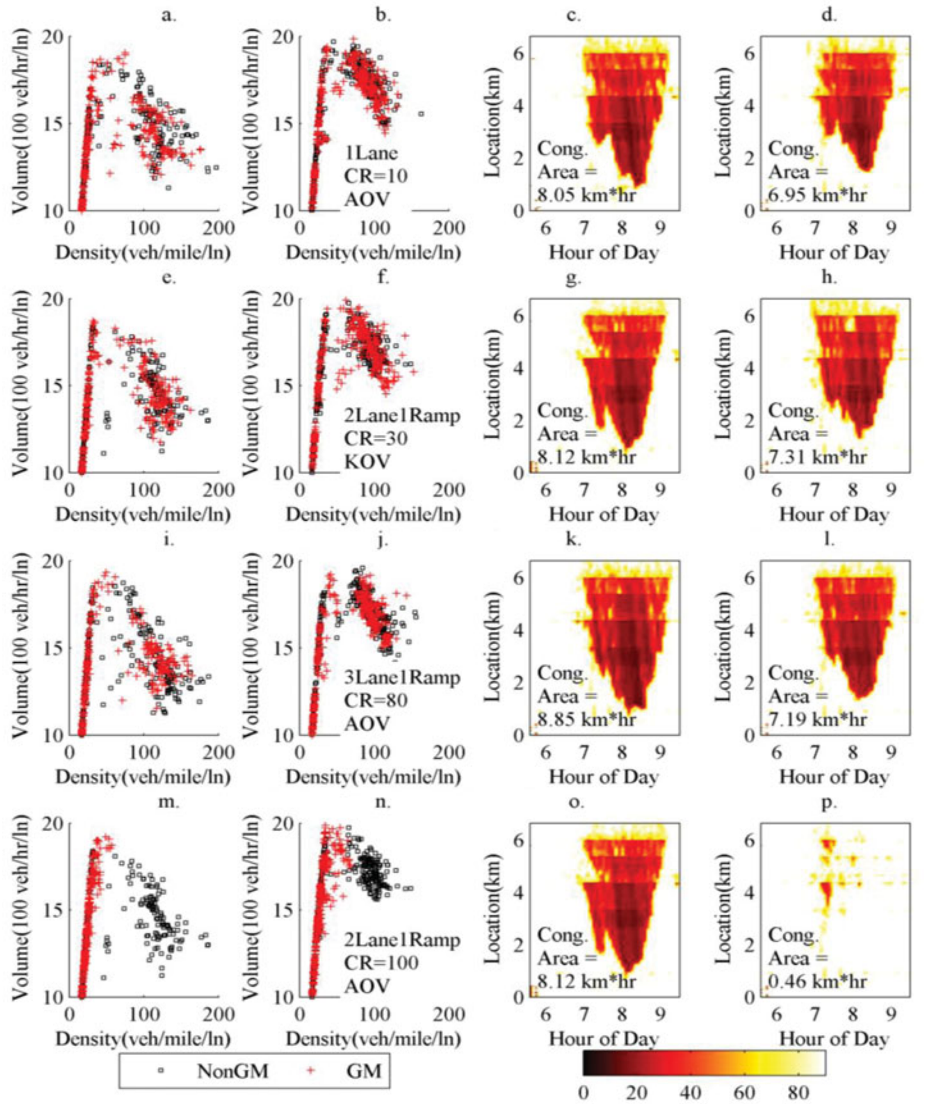
Table 1. Network delay reduction per vehicle for different gap metering scenarios.

	Mainline only, "Allow-one-vehicle-in-front"				
Lane \ *CR	10	30	50	80	100
1	− 11.1%	− 8.8%	− 7.8%	− ***3.7%***	− ***2.3%***
2	− 9.7%	− ***12.5%***	− ***0.7%***	− 6.2%	52.9%
3	− ***3.6%***	− 8.9%	− ***0.7%***	− 10.2%	45.9%
	Mainline only, "Keep-one-vehicle-gap"				
Lane \ CR	10	30	50	80	100
1	− 9.5%	− 7.8%	− 7.9%	− 6.6%	− 10.2%
2	− 8.6%	− 8.7%	− ***4.1%***	− 10.6%	63.0%
3	− 6.8%	− ***2.9%***	− ***4.1%***	− ***13.7%***	55.5%
	With ramp, "Allow-one-vehicle-in-front"				
Lane \ CR	10	30	50	80	100
1	− 6.9%	− 11.1%	− 9.6%	− 14.6%	− 61.8%
2	− 6.8%	− 6.3%	− 9.3%	− 20.4%	− ***62.5%***
3	− 6.8%	− 6.3%	− 9.3%	− 20.4%	− 62.5%
	With ramp, "Keep-one-vehicle-gap"				
Lane \ CR	10	30	50	80	100
1	− 12.0%	− 12.3%	− 12.5%	− 24.5%	− 61.8%
2	− 10.1%	− 12.1%	− 9.3%	− 27.5%	− ***62.2%***
3	− 10.1%	− 12.1%	− 9.3%	− 27.5%	− 62.2%
	Ramp metering only				
Ramp	− 5.2%				

*CR: Compliance rate. *Italic*: Delay reduction less than ramp metering only.

Four representative scenarios are shown in Figure 5 to evaluate both the fundamental diagrams (volume-density plot) and the speed contour maps. The selected scenarios and the corresponding subfigure indexes are as follows:

- Scenario A (6.a-d): 10% compliance, metered mainline rightmost lane, AOV, 222 as the random seed for simulation run.



* GM: Gap Metering, Cong. Area: Congested Area on Speed Contour Map (km*hr)

Figure 5. Fundamental diagram and speed contour map analysis.* GM: gap metering; Cong. Area: congested area on speed contour map (km*hr) a. Beloit Rd. b. National Ave c. Baseline Speed(Km/h) d. GM speed(km/h) e. Beloit Speed f. National Ave g. Baseline Speed(Km/h) h. GM speed(km/h) i. Beloit Rd. j. National Ave k. Baseline Speed (Km/h) i. GM speed(km/h) m. Beloit Rd. n. National Ave o. Baseline Speed(Km/h) p. GM speed(km/h).

- Scenario B (6.e-h): 30% compliance, metered mainline right two lanes and on ramp, KOV, and 122 as the random seed for simulation run.
- Scenario C (6.i-l): 80% compliance, metered mainline right three lanes and on ramp, AOV, 22 as the random seed for simulation run.
- Scenario D (6.m-p): 100% compliance, metered mainline right two lanes and on ramp, AOV, 122 as the random seed for simulation run.

Fundamental diagrams at the merging areas (Beloit Rd. and National Ave.) for both with and without GM are plotted to investigate the distribution of traffic states and the transition region where traffic breakdown occurs. It is found that with an increase in the compliance rate, gap metered merging areas exhibit higher capacity at the transition areas between free flow and congested flow. When full compliance on the mainline is achieved and vehicles on the ramp are gap metered, congested traffic states can be significantly reduced during peak hours. To study the impact of GM on the corridor, the speed contour maps for the entire NB segment of I-894 (the location of the recurrent bottleneck) are plotted. To quantify the congestion reduction, the diagram also contains calculated size of the congested area with speeds below 35 mph (56.3 km/h). The results indicate a significant congestion reduction and in the most ideal scenario (full compliance, both mainline and ramp are gap metered), the deactivation of the recurrent bottleneck. Based on the aforementioned

Table 2. Performance comparison for different control strategies.

Freeway mainline condition				
	Base case	Ramp metering only	Gap metering only	Ramp and gap metering
Average delay (s)	519	483 (−7%*)	392 (−24%)	344 (−34%)
Throughput (vehicles)	4047	4074 (1%)	3937 (−3%)	3970 (−2%)
Speed (km/h)	12.78	13.52 (6%)	15.8 (24%)	17.6 (38%)
Mean travel time (s)	649	613 (−6%)	523 (−19%)	474 (−27%)
Frontage road condition				
	Base case	Ramp metering only	Gap metering only	Ramp and gap metering
Average delay (s)	340	344 (1%)	325 (−4%)	313 (−8%)
Throughput (vehicles)	83	81 (−2%)	75 (−10%)	75 (−10%)
Speed (mph)	17.6	17.5 (−1%)	18.2 (3%)	18.7 (6%)
Travel time (s)	470	474 (1%)	455 (−3%)	443 (−6%)

Note. * Relative difference = (control case − base case)/(base case).

results, we selected the most cost-effective control strategies of AOV on the rightmost lanes with 10% compliance rate.

The I-35 NB performance comparison

The evaluation on the I-35 NB corridor uses the conservative implementation scenarios the AOV implemented at the rightmost general purpose lane with a compliance rate of 20%. The GM and ramp metering system are implemented at the two weaving and one on-ramp only location. Three evaluation scenarios are tested including ramp metering only, GM only, and ramp and GM. The ramp metering algorithm implemented is the ALINEA based on VisVAP implementation from a previous Texas DOT project (Chaudhary, Tian, Messer, & Chu, 2004). An optimal occupancy threshold 0.31 is calibrated to achieve the optimal performance. We run the simulation with ten random seeds, the results are evaluated by comparing the average vehicle delay, throughput, average speed, and average travel time.

Table 2 compares the system performance under different control scenarios with both the observed values and their relative percentage changes with respect to the base case. GM system can reduce total network delay by 24% including frontage roads and reduce delay by 34% if coordinated with ramp metering, while ramp metering alone can reduce only 7% of the total network delay.

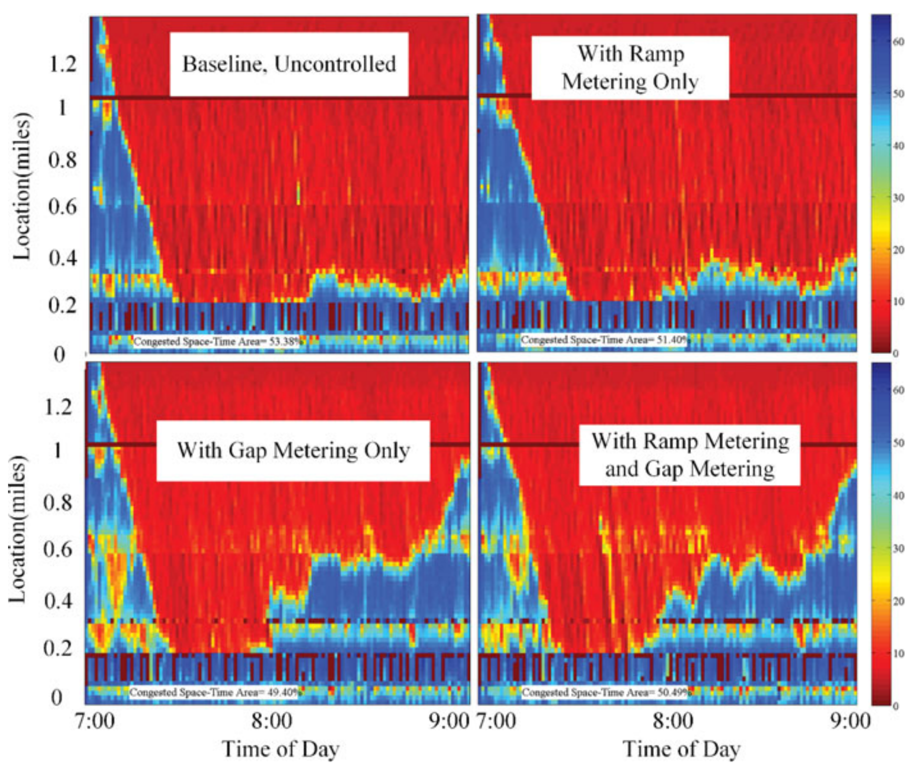


Figure 6. Space-time congestion diagram comparison (Seed 322).

Figure 6 further illustrates the congestion reduction and early recovery caused by GM using the space-time speed contour map based on the results from the run of seed 322. The horizontal axis is the time of day. The vertical axis is location along the freeway main line. The color in each grid of the space-time diagram indicates the speed. Blue region indicates free flow and red region indicates congestion, and the area of the congested region indicates the scale of the traffic congestion. It can be observed that GM significantly reduced the congested region on the space-time diagram, allowing for earlier recovery of traffic flow during the peak hours.

Conclusions and future work

In this study, a new ATDM strategy is proposed for freeway recurrent and non-recurrent merge control by managing the gaps of mainline traffic flow. GM systems are suited to aid traffic flow at recurrent and non-recurrent bottlenecks caused by heavy merging. The system design, control framework, and traffic flow characteristic aspects of GM are discussed in detail. The control system is implemented using VISSIM COM API on a calibrated model for two freeway corridor with active recurrent bottlenecks. The evaluation results of the proposed system on two different freeway corridors located in Wisconsin and Texas demonstrate the generality of the proposed system to smooth traffic in merger zones and decrease the average vehicle delay. The simulation shows a decrease in corridor average delay around 24% even at a compliance rate of only 20%. The congested region of traffic flow on the space-time diagram also reduces significantly. These results indicate a promising potential for the proposed control system. Furthermore, an evaluation study is conducted to compare GM with the ALINEA ramp metering technologies. The results illustrate the potentials of using GM as an effective alternative in addressing traffic congestion caused by merging traffic. GM alone outperforms the ramp metering system with 17–27% more delay reduction and can help improve the performance of ramp metering system.

Admittedly, several limitations exist in this study. First, the proposed system is only evaluated using microsimulation although with different behavioral and compliance scenarios. Field testing of such systems may reveal more issues and concerns not addressed within this article. In the simulation study, a fixed amount is added to the parameter CC0 in the VISSIM Wiedenmann 1999 model (Karlsruhe & AG, 2011) to implement the increased gap. Such simplified implementation may or may not be consistent with real-world driver behavior, which needs to be validated with empirical studies. As indicated in Table 1, as with many other control systems, when inappropriately configured, the GM system may cause more congestion (e.g., when full compliance is achieved) when its capacity reduction impact overwhelms its traffic calming impact. Such scenarios are found to occur when the GM is implemented for multiple general purpose lanes on the mainline with full driver compliance but not coordinated appropriately with metering strategies on the ramp.

Future work on this system will be conducted from several directions. First, an adaptive control logic can be developed to respond to the prevailing gap conditions at merging areas. Second, the control signal design must be refined and improved with more consideration given to human factors (e.g., perception error of spacing) and driver compliance. Third, further field- or simulator-based behavioral studies need to be conducted to understand the behavioral impact of through-lane vehicles. For example, how frequent through-lane vehicles will merge to inner lanes to avoid GM. Further exploration can also be carried out to study how GM system can interact with other ATDM systems such as ramp metering and variable speed limit. Although evaluated with recurrent congestion scenarios, the proposed methods can also be used against work zones, incidents, and other non-recurrent congestion scenarios that triggered by merging traffic flow. Further testing and evaluation can be conducted by simulating and field testing this idea.

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