REAL-TIME WORK ZONE MANAGEMENT FOR THROUGHPUT MAXIMIZATION

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ABSTRACT

A simple control concept is proposed for efficient real-time work zone management in cases where the arriving flow exceeds the capacity of the work zone, leading to congestion and reduced efficiency due to capacity drop. Merging traffic control is proposed so as to maintain the occupancy (or the number of vehicles) in the merge area close to a critical value that maximizes throughput; to this end, an algorithm known from local ramp metering operations is employed (ALINEA). The potential control concept efficiency is demonstrated by use of microscopic simulation applied to a hypothetical work zone infrastructure with and without merging traffic control. It is shown that the employed feedback regulator is little sensitive to various settings which indicates easy applicability with low fine-tuning needs in potential field applications.

Keywords: Work zone management; ALINEA; merging traffic control; traffic control

INTRODUCTION

Work zones on freeways necessitate the drop of one or more lanes at the work zone entrance which may create traffic flow disruptions and congestion upstream of the work zone due to reduced capacity. Work zone management aims at smooth, safe and efficient passage of vehicles, with particular focus on the work zone entrance where vehicles need to merge into fewer lanes. Proposed management measures for work zones include speed limitations as well as signing, markings, geometric design (*1, 2*).

Vehicles approaching the work zone need to merge into a lower number of lanes. When the arriving flow is lower than the flow capacity of the work zone, the merging efficiency is usually satisfactory and there is no need for external intervention in real time. If the arriving flow reaches or exceeds the work zone capacity, a congestion is created in the merging area, and the work-zone entering flow is reduced below the work-zone capacity due to the capacity-drop phenomenon. Under these conditions, real-time control of the arriving flow may be employed so as to guarantee a maximum exit flow from the merge area. This is similar to local ramp metering measures where, in contrast, only a part of the arriving traffic flow is controlled so as to maximize the merge area throughput.

This paper proposes a real-time merging traffic control scheme for work zone management aiming at throughput maximization (or, equivalently, at average delay minimization, or, equivalently, at upstream queue minimization) when the arriving flow exceeds the work zone capacity. The scheme employs local ramp-metering like algorithms, in particular ALINEA (*3*). The proposed control scheme may be viewed as an instance of a more general frame for real-time merging traffic control developed recently (*4*). The concept is tested in this paper by use of microscopic simulation so as to demonstrate the potentially achievable benefits.

REAL-TIME WORK ZONE MANAGEMENT CONCEPT

Structure and Elements

The proposed real-time merging traffic control system for freeway work zones (Figure 1) comprises a number of general elements, each of which may take different forms or options:

(i) Arriving flow and queuing area (total of M lanes)
(ii) Work zone (μ lanes, $\mu < M$)
(iii) Merge area
(iv) Control devices
(v) Real-time measurements or estimates
(vi) Control algorithm.

Each of these elements will be discussed in the following with regard to its characteristics and possible options.

Arriving Flow, Queuing and Work Zone Infrastructures

The arriving traffic flow approaches the work zone on a number M of lanes. If the arriving traffic flow occasionally exceeds the work zone capacity, then queuing is inevitable. Within the queuing area (Figure 1), lane-changing may be:

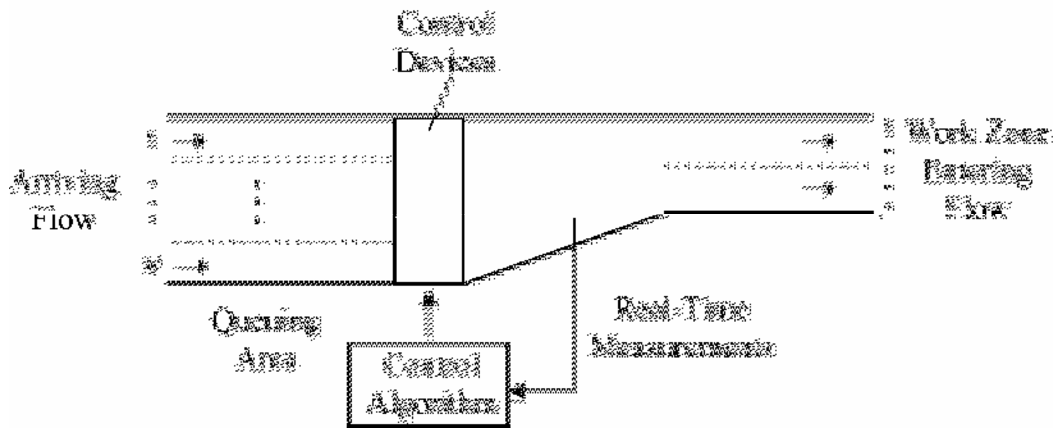

FIGURE 1 A general real-time merging traffic control system for toll plazas with M entering and μ exiting lanes, $\mu<M$.

- Fully allowed, in which case it is reasonable to assume that the individual lane queues will tend to be balanced, provided the individual lane flows (and hence the queue waiting times) are similar to each other;
- Not allowed, in which case individual lanes may have queues (and waiting times) that are different from each other.

After merging from M to μ lanes, vehicles enter the work zone with μ lanes and corresponding flow capacity q_{cap}. It is assumed that the work zone flow capacity q_{cap} is (occasionally) lower than the maximum arriving flow, otherwise merging traffic control cannot improve the system efficiency.

Merge Area

The vehicles arriving on M lanes, change lanes appropriately within the (typically trapezoidal) merge area so as to fit into the μ lanes of the exit. The merging procedure may be quite complex in terms of the required vehicle maneuvers which may be a challenge for microscopic models and simulators. Indeed, the lane-changing component is a notorious weak point of microscopic simulators, particularly when applied to special merging traffic infrastructures as work zones (*5*).

Fortunately, the complexity of microscopic vehicle merging behaviors does not reflect on the real-time merging traffic control actions envisaged here, because the basic assumption that justifies real-time merging traffic control is of a macroscopic nature and is related to the well-known notion of a fundamental diagram. Figure 2 displays a typical flow-density diagram for the merge area, where the flow q_{out} is the merge area exit flow and N is the number of vehicles included in the merge area (or in the downstream part of the merge area). When N is small, merging conflicts are scarce and swift, while the exit flow is correspondingly low. As N increases, merging conflicts may increase, but q_{out} increases as well until, for a specific value N_{cr}, the exit flow reaches the downstream capacity q_{cap}. If N increases beyond N_{cr}, merging conflicts become more serious, leading to substantial vehicle decelerations and eventual accelerations that reduce the exit flow to lower values q_c, where $q_{cap}-q_c$ is the capacity drop due to congestion (*4*).

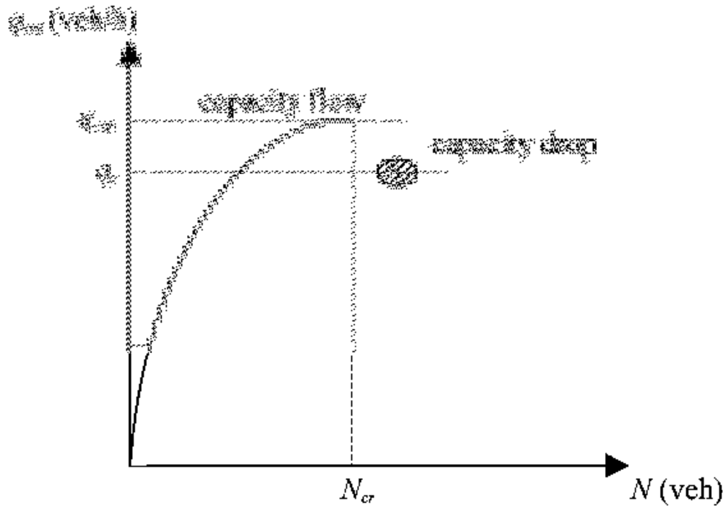

FIGURE 2 Fundamental diagram of a merging area.

Real data analysis from freeway on-ramp merge areas revealed that traffic breakdown may occur at different flow values q_{cap} on different days, even under similar environmental conditions (*6*, *7*). Naturally, flow capacity differences become even more pronounced in case of adverse environmental conditions (*8*). In contrast, the critical occupancy (at which capacity flow occurs) was found to be fairly stable (*7*) even under adverse environmental conditions (*8*, *9*). These findings suggest the introduction of a control scheme that would act on the arriving traffic flow so as to maintain (whenever necessary) the number of vehicles N in the merge area close to its critical value N_{cr}, thus maximizing the exit flow q_{out}, i.e. optimizing the merge infrastructure efficiency. This is a usual ramp metering practice, e.g. by use of the local ramp metering strategy ALINEA (*3*).

Control Devices

An appropriate control device to regulate the arriving flow for work zone management are traffic lights positioned upstream of the merge area (Figure 1); the distance between the traffic lights and the merge area should be sufficiently long so as to allow for queuing vehicles to accelerate sufficiently towards efficient merging. Traffic lights may be applied to individual lanes separately or to all lanes simultaneously. If very short cycles are applied (e.g. one or two cars per green per lane), queuing cars may be continuously moving (albeit at low speed) without actually stopping.

Alternatively, variable speed limits or emerging infrastructure-vehicle systems may be used for traffic flow control upstream of the merge area.

If necessary, control devices may be installed only on a part of the entering lanes while traffic flow on other lanes is allowed to enter the merge area freely (e.g. by-pass lanes for HOV, buses, emergency vehicles).

Real-Time Measurements or Estimates

Application of feedback control so as to maintain the number of vehicles N close to N_{cr} calls for availability of real-time measurements or estimates of N. Although this quantity may be directly measurable by use of video sensors, this possibility may be costly or difficult. An alternative possibility would be the real-time estimation of N by use of a limited number of ordinary loop detectors (*10*).

Yet another possibility would be to consider the easily measurable occupancy o, rather than the number of vehicles N, as the variable under control. As a matter of fact, the diagram of Figure 2 is valid for occupancy as well (and occupancy rather than N is typically used for ramp metering operation). This raises the question on the specific location where the occupancy should be measured. The occupancy measurement should best be placed at or just upstream of the location where serious vehicle decelerations (congestion) appear first. This is because congestion, once occurred, propagates upstream, thus the measurements feeding the control algorithm should be placed:

- not downstream of the location where congestion appears first, otherwise the congestion is not visible and the control goal $(o \approx o_{cr})$ may not be achievable;
- as close upstream of that location as possible, so as to minimize delays in the triggered control reaction.

Usually, merge congestions in freeway on-ramp merge areas appear first a few hundred meters downstream of the ramp nose, which is, in most cases, downstream of the acceleration lane drop (*5*). In contrast, microscopic simulators create the merge congestion typically at the acceleration lane-drop location.

In conclusion, the functional merge area for pertinent merging traffic control may be different than the physical merge area. More specifically, the functional merge area for control may have to be extended downstream to cover the location of first congestion appearance, which, in some cases, may be within the work zone.

Control Algorithm

The control algorithm receives the real-time measurements or estimates of N or o and drives the control devices so as to maintain $N \approx N_{cr}$ or $o \approx o_{cr}$ which maximizes the merge area exit flow. This is the major control goal, but there may be alternative and secondary control goals as discussed in this section. The overall control algorithm may be decomposed into three distinct parts, each with individual duties:

a) Feedback control for merge area exit flow regulation (ALINEA)
b) Distribution of entering flows
c) Translation of control decisions

to be discussed in the following.

a) Feedback Control

This is the central task of the control algorithm; it is activated at each time interval T, whose value may be selected within the range [20 s, 60 s]. More specifically, at the end of each running period T, time-averaged measurements of occupancy o from the ending period (or the latest measurements or estimates of vehicle-number N) are used to calculate the entering flow to be implemented (via the control devices) in the next period in the aim of maintaining $o \approx o_{cr}$ (or $N \approx N_{cr}$). This may be achieved by use of the well-known integral feedback (I-type) ALINEA regulator (*3*)

$$q(k) = q(k-1) + K_R[\hat{o} - o(k-1)] \tag{1}$$

where:

- $k = 1, 2, ...$ is the discrete time index;
- $q(k)$ is the controlled entering flow (veh/h) to be implemented during the new period k;
- $o(k-1)$ is the last measured occupancy (%) averaged over all lanes;
- $K_R > 0$ is a regulator parameter;
- $\hat{o}$ is the set (desired) value for the occupancy which may be set equal to o_{cr} for maximum exit flow.

The flow $q(k)$ resulting from Equation 1 is truncated if it exceeds a range $[q_{\min}, q_{\max}]$ where $q_{\min} < q_{cap} < q_{\max}$, and the truncated value is used in Equation 1 as $q(k-1)$ in the next time step to avoid the well-known wind-up effect of I-type regulators. The range $[q_{\min}, q_{\max}]$ should be sufficiently wide to enable flexible control without frequent bound-hitting during the peak hours. On the other hand:

- $q_{\max}$ should not be too large; this is because Equation 1 is easily seen to lead the calculated q to upper-bound saturation (i.e. $q(k) \equiv q_{\max}$) if $o < \hat{o}$ for a sufficiently long period (e.g. during off-peak), while the actual inflow q_{in} is lower; when o eventually exceeds $\hat{o}$ (at the start of the peak hour), the calculated q is gradually reduced via Equation 1, but an actual reduction of the entering flow is only achieved when q becomes smaller than the current inflow q_{in}; this may take some time steps, the number of which is obviously larger for larger $q_{\max}$ (and lower K_R in Equation 1); during this transient period, o continues to increase, and an overshoot (i.e., a negative regulation error $\hat{o} - o(k-1)$) is created, whose magnitude and duration increases with increasing $q_{\max}$, due to the corresponding increase of the transient period.
- $q_{\min}$ should not be too small to avoid any (temporarily) strong strangulation of the entering traffic flow.

Reasonable values, as a trade-off of the mentioned aspects, are $q_{\max} \approx 1.2\, q_{cap}$ and $q_{\min} \approx 0.5\, q_{cap}$.

The feedback algorithm leads to a stable closed-loop behavior (*11*) for a broad range of positive K_R values. In the steady-state (stationary conditions), we have in Equation 1 $q(k) = q(k-1) = \overline{q}$ and hence $o(k-1) = \overline{o} = \hat{o}$, i.e. exact regulation. Due to the integral-feedback character if Equation 1, stationary accuracy is achieved even if there are errors in the implementation of the calculated q (e.g. due to traffic light operation inaccuracies, red-light violations, by-pass lanes for buses or HOV), see (*3*).

The usual control goal in case of local control is outflow maximization with $\hat{o} = o_{cr}$ (or $N = N_{cr}$) in Equation 1. The precise value of o_{cr} (or N_{cr}) may depend on the specific infrastructure and measuring devices and can be identified experimentally. Alternatively, one may employ a real-time estimator for these quantities, e.g. as proposed in (*12*).

The control results are little sensitive to the specific value of K_R within a broad range of values. As a rule-of-thumb, K_R in (1) should be higher than $25 \cdot \mu$ veh/h/%.

In some cases, a portion of the *M* arriving lanes may not be controllable, e.g. some by-pass lanes for HOV or buses. In these cases, q in Equation 1 reflects the flow on the controllable arriving lanes only, while the uncontrollable flows act as disturbances that do not need to be taken into account in the control algorithm thanks to its feedback character.

b) Distribution of Entering Flow

The feedback regulator delivers, at each time step T, the total flow values q to be implemented at the controllable entering lanes during the next period. How should this total flow be distributed among individual (or among groups of) controllable entering lanes? This question cannot be answered in a general way as it may depend on various characteristics of the merging infrastructure. Here are some examples:

- Consider a work zone where lane-changing is possible in the queuing area; an equal distribution of q among the entering lanes seems reasonable.
- Consider a work zone where lane-changing is not allowed or not possible in the queuing area (e.g. due to physical separation); it may then be reasonable to distribute q among the entering lanes in a way that equalizes the lane queues or the corresponding waiting times. This may call for feedback control with real-time measurements or estimates of queue lengths.

c) Translation of Control Decisions

At the end of parts a) and b) at each time step *T*, each controllable entering lane (or each group of lanes with one common control device) has an assigned subflow q_i that needs to be implemented via appropriate activation of the corresponding control device. The specifics of this translation of the control decisions into control device actions cannot be specified in a general form. Even for the same control device, there may be different possible operational policies; e.g. for traffic lights we may have one-car-per green, n-cars-per-green, full traffic cycle, discrete release rates etc., see (*13*). A two-cars-per-green-per-lane policy is employed in the following simulation investigations.

SIMULATION SETUP

The hypothetical infrastructure considered in order to demonstrate, via microscopic simulation, the potential of real-time work zone management, features $M = 3$ arriving lanes and is sketched in Figure 3a. Traffic arrives on 3 lanes and reaches, after 685 m, the trapezoidal merging area (20 m) followed by the work-zone restricted freeway with 1 lane and (empirical) capacity $q_{cap} \approx 2300$ veh/h. Lane changing is possible on the arriving freeway lanes.

The specific arrival demand scenario considered is stochastic; the average demand starts at level zero (in an empty freeway) and increases linearly to 2500 veh/h (which exceeds the work area capacity q_{cap}) within the first 10 minutes; during the next 10 minutes, the average demand is maintained constant at this high value (peak hour); during time $t \in [20 \text{ min}, 30 \text{ min}]$, the demand reduces linearly back to zero and then maintains zero demand until the end of the investigation (40 min) in order to have an empty system again. This scenario includes a total of about 830 veh served.

The feedback algorithm (Equation 1) is used for merging traffic control by use of occupancy measurements collected just upstream the trapezoidal merge area (Figure 3a). The regulator is activated every $T = 30$ s, and the required bounds are set $q_{\min} = 1000$ veh/h and $q_{\max} = 3000$ veh/h. The flow value q delivered by Equation 1 is eventually distributed evenly among the three entering lanes by use of three respective traffic lights (one per lane) that are placed 50 m upstream of the merge area (Figure 3a). Each traffic light has a constant green phase of 4 s that allows in average some 2 vehicles to pass. A signal cycle c (in s) consists of a (constant) green phase and a (variable) red phase and allows some 2 vehicles to pass. Thus, the implementation of a flow q (veh/h) calls for a traffic cycle (equal for all lanes) that satisfies

$$q = (2 \cdot M / c) \cdot 3600 \Rightarrow c = 7200 \cdot M / q. \tag{2}$$

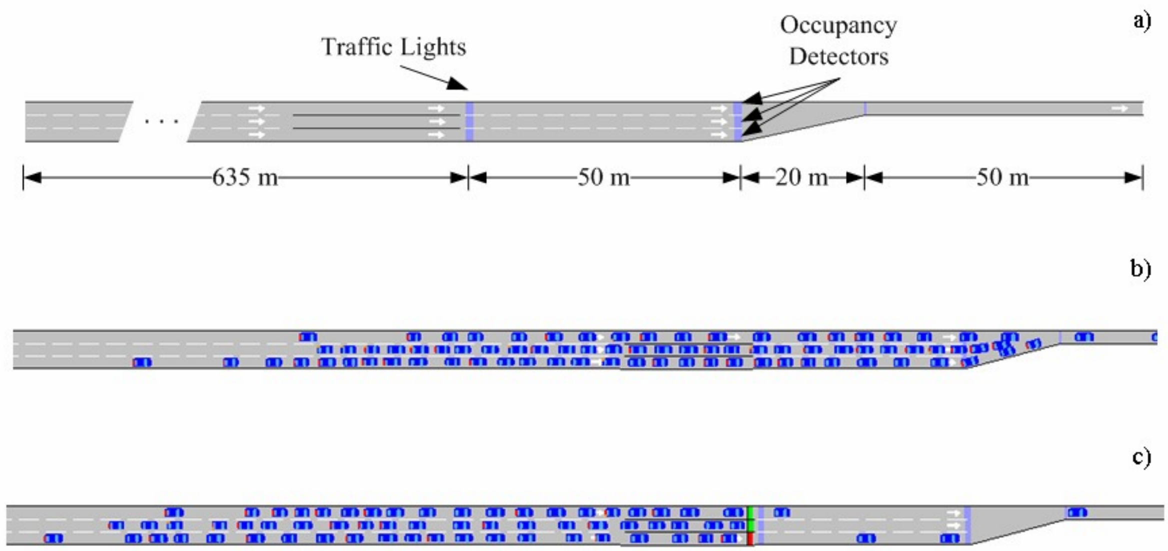

FIGURE 3 (a) A work zone infrastructure; (b) screenshot of simulation without control (*k*= 34); (c) screenshot of simulation with merging traffic control (*k*= 34).

The cycle length resulting from Equation 2 is rounded off to the next integer value (in s). The red phase is not allowed to be lower than 2 s, hence there is a minimum cycle length $c_{\min} = 6$ s, and c resulting from Equation 2 is truncated if it is lower than $c_{\min}$. Note that $c_{\min}$ is never reached here since $q_{\max} = 3000$ veh/h delivers $c = 7.2$ s in Equation 2.

To avoid bursty entering flows that may appear if all three traffic lights assume their green and red phases simultaneously, a shift (offset) is introduced for the cycle start of each traffic light relative to the cycles of the other traffic lights.

Note that the regulator time step T is not an integer-multiple of the cycle c in general, which creates a synchronization problem that is solved as follows. As soon as $q(k)$ is delivered by the feedback algorithm, the corresponding cycle $c(k)$ is calculated via Equation 2. This cycle is held for application at the end of the last (running) cycle $c(k-1)$ of the previous period $k-1$. The resulting implementation error is deemed minor, particularly in view of the automatic disturbance-rejection property of Equation 1 mentioned in the last section.

The described infrastructure was simulated by use of the microscopic simulator AIMSUN NG Professional Edition 5.1.1 using the simulator's default parameters and a simulation time step of 0.75 s. The simulation infrastructure had to be constructed from available elements since traffic simulators do not include complete work zone components. The trapezoidal merging area (Figure 3a) is modeled as a 'junction', and the occupancy-measuring loop detectors are placed just upstream of that junction (Figure 3a), since AIMSUN does not allow for placement of detectors within 'junctions'.

The simulated merging traffic control software is interfaced with the simulator via the AIMSUN API (Application Programming Interface) that allows us to emulate a real-time closed-loop operation. More specifically, the simulator delivers every T the occupancy (averaged over the three lanes), based on which the control software calculates the corresponding traffic light settings and returns them to the simulator for application.

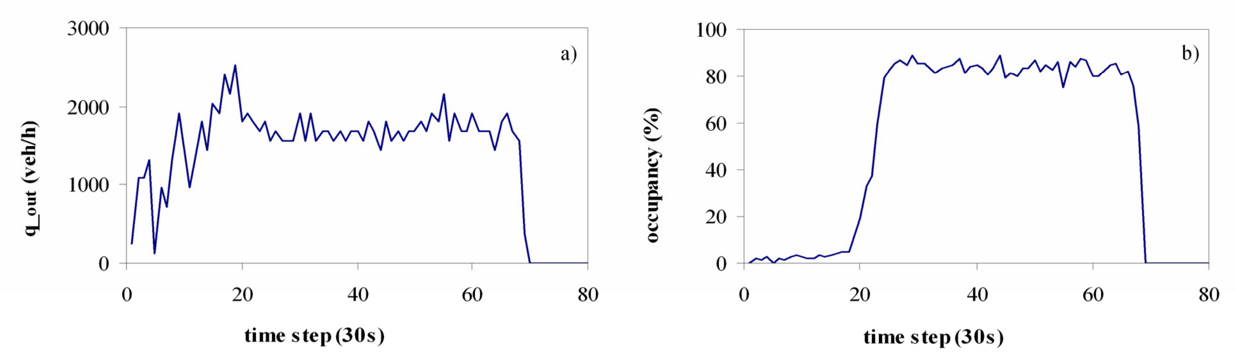

FIGURE 4 Outflow q_{out} (a) and occupancy o; (b) in the no-control case.

The merging behavior of vehicles is a well-known weak point of microscopic simulators (*5*), particularly in the case of somewhat unusual merging infrastructures. Therefore, the produced simulation results should be understood as a demonstration of potential benefits achievable via merging traffic control, rather than as a quantitatively reliable assessment of achievable benefits.

Since AIMSUN is a stochastic simulator, different runs with different seeds may produce quite different results. To address this issue, the usual practice is to run several simulations, each with different seed, for each simulated scenario. This practice is followed in the reported investigations with 10 replications per scenario. The main evaluation criterion used is the average vehicle delay (AVD) (in s/veh/km) that is delivered by AIMSUN.

SIMULATION RESULTS

In the no-control case, the arriving vehicles continue their trip in the merge area and exit without noteworthy problems as long as the arriving demand is lower than the work area capacity q_{cap}. When the arriving demand approaches q_{cap}, serious vehicle merging conflicts with strong vehicle decelerations are observed that lead to the formation of a congestion in the merge area; the congestion spills back onto the three entering lanes without ever reaching the simulated system entrance. The congestion is captured by the occupancy detectors when it reaches the corresponding location (Figure 3a). The mean of the resulting average vehicle delays (in s/veh/km) for 10 replications is 217 with a standard deviation of 38.8, and highest/lowest AVD values of 269/158, respectively.

Figures 4a and 4b display the trajectories of the merge area outflow q_{out} and occupancy o, respectively, for one particular simulation run with AVD = 217 s/veh/km (i.e. equal to the mean AVD of 10 replications). The outflow q_{out} is roughly following the arriving demand increase until about $k = 20$ where it shortly approaches the capacity q_{cap}. The occupancy o is increasing slowly (due to increasing flow) during the same period. After $k = 20$, the occupancy has a steep increase (due to the formed congestion) and stabilizes eventually at a value around 85%; at that state, the merge area is full of vehicles due to congestion. Soon after the first appearance of the congestion (i.e. after $k = 20$) the outflow reduces (capacity drop) to values around 1800 veh/h. Figure 3b displays a screenshot of a simulation run at $k = 34$; it may be seen that the merge area is full and queues extent upstream of the merge area. When the demand is decreased and the formed queue is served, the system is emptied (at around $k = 70$).

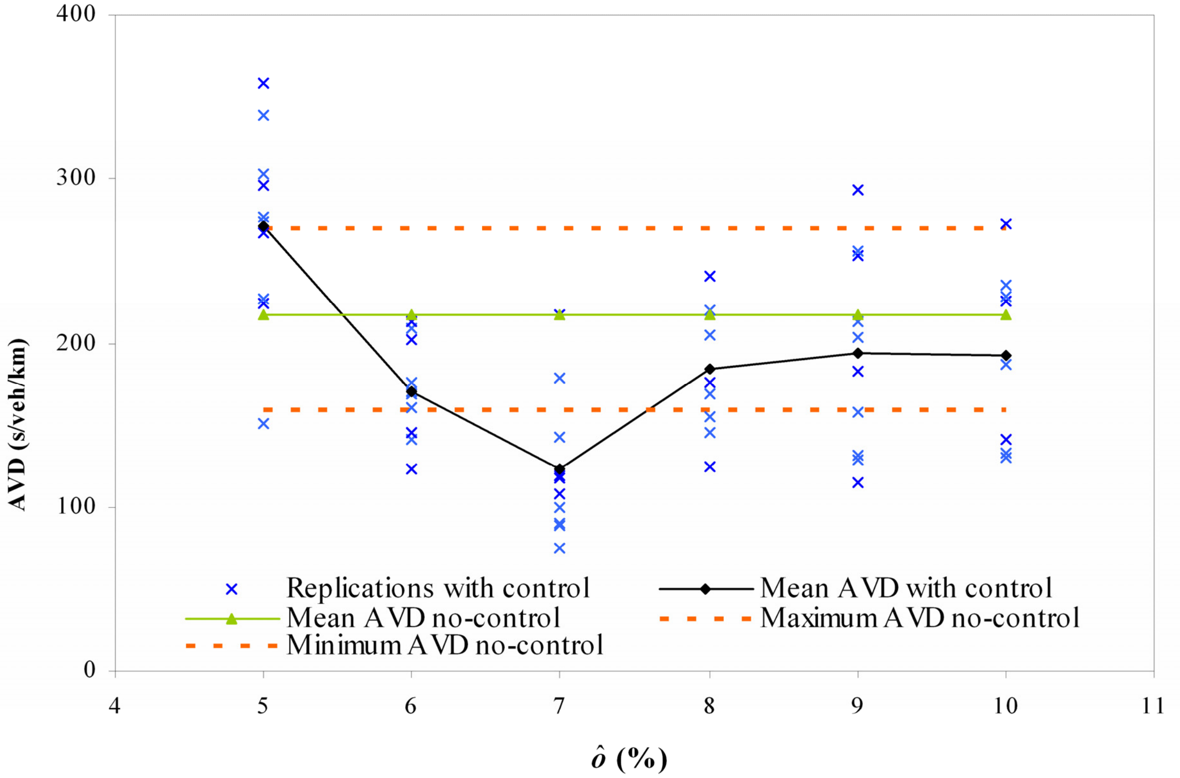

FIGURE 5 Average vehicle delay versus $\hat{o}$ with and without merging traffic control.

When merging traffic control is applied, the traffic lights are initially operated with a short red phase (corresponding to $q_{max} = 3000$ veh/h) for as long as o is lower than the set value $\hat{o}$, according to Equation 1. Note that some slight delays may occur to some vehicles that encounter the red phase, but there are no real queues in front of the traffic lights, and the merge area outflow is mainly determined by the arriving demand (no real metering). The slight delays could be avoided if the traffic lights are switched on only when needed (i.e., when o approaches $\hat{o}$). As the arriving demand increases, o increases, and, when $o(k) > \hat{o}$, the regulator (Equation 1) starts its actual arriving flow control operation aiming at maintaining $o(k)$ near $\hat{o}$. At this time, a queue is formed upstream of the traffic lights which increases, without ever reaching the simulated system entrance. Figure 3c displays a simulation screenshot (at $k = 34$) with the formed queues. By visual inspection, the number of queuing vehicles in Figure 3c is lower than in Figure 3b due to higher outflows in the merging traffic control case.

As mentioned earlier, the ultimate goal of merging traffic control is the merge area outflow maximization which leads to minimization of the average delay. Outflow maximization is achieved via an appropriate specification of $\hat{o}$ in Equation 1. To investigate this issue, a series of simulation runs were carried out with different $\hat{o}$-values and 10 replications for each such value; the utilised K_R value in Equation 1 is initially set equal to 100 (veh/h/%). Figure 5 displays some of the obtained results in terms of the average vehicle delay (AVD); more specifically, Figure 5 displays, for each investigated $\hat{o}$-value in the range [5% , 10%], the AVDs of the 10 simulation replications and the corresponding mean AVD value. For comparison, Figure 5 also displays (horizontal lines) the mean, highest and lowest AVD values of the 10 replications of the no-control case.

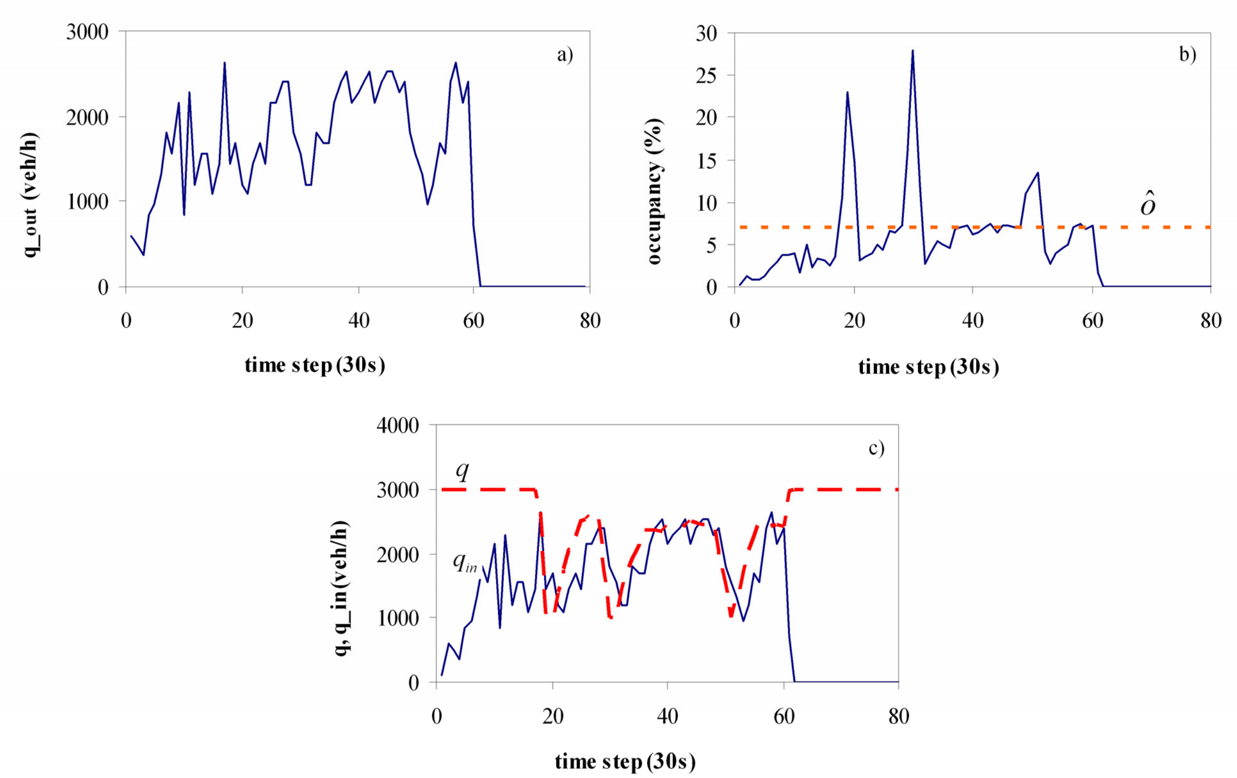

FIGURE 6 Merging control case with $\hat{o}$ = 7 % veh, K_R = 100 veh/h/%: (a) outflow q_{out}; (b) occupancy o; (c) ordered q and actual q_{in} inflow into the merge area.

It may be seen in Figure 5 that the mean AVD under control is minimized for $\hat{o} = 7\%$. At first view, this value may appear very low for a critical occupancy; recall, however, that o is measured on three lanes (Figure 3a) to maximize the flow of one single lane (downstream). The mean AVD is lower than its no-control counterpart for all $\hat{o}$ except $\hat{o} = 5\%$; the mean AVD for $\hat{o} = 7\%$ is 123 s/veh/km which is 43% lower than the mean AVD of the no-control case. Notice, however, that, there are some control replications with a higher AVD than the best no-control AVD, even for the optimal set-point $\hat{o} = 7\%$.

Figures 6a and 6b display the trajectories of q_{out} and o, respectively, for one particular simulation run with $\hat{o} = 7\%$ and AVD = 118 s/veh/km which is close to the mean AVD of the corresponding 10 replications. The outflow q_{out} is roughly following the arriving demand increase until about $k = 18$, at which time o exceeds $\hat{o}$ and the regulator (Equation 1) is activated; for reasons mentioned earlier, o exhibits a strong overshooting (reaching 20%), followed by an undershooting.

The regular control period after the initial overshooting is characterized by occasional, randomly appearing, significant departures of the occupancy under control to values that may reach 30% or more. The observed occupancy spikes are due to occasionally appearing (simulated) vehicle merging conflicts that lead to provisionally strong vehicle decelerations in the merge area, i.e. small congestions that are captured by the occupancy detectors; this triggers a corresponding regulator reaction (inflow reduction) that drives the occupancy back to values close to $\hat{o}$, albeit with a corresponding undershooting. Thus the regular merging control period (after the transient period) comprises a number of short-lived occupancy spikes and eventual

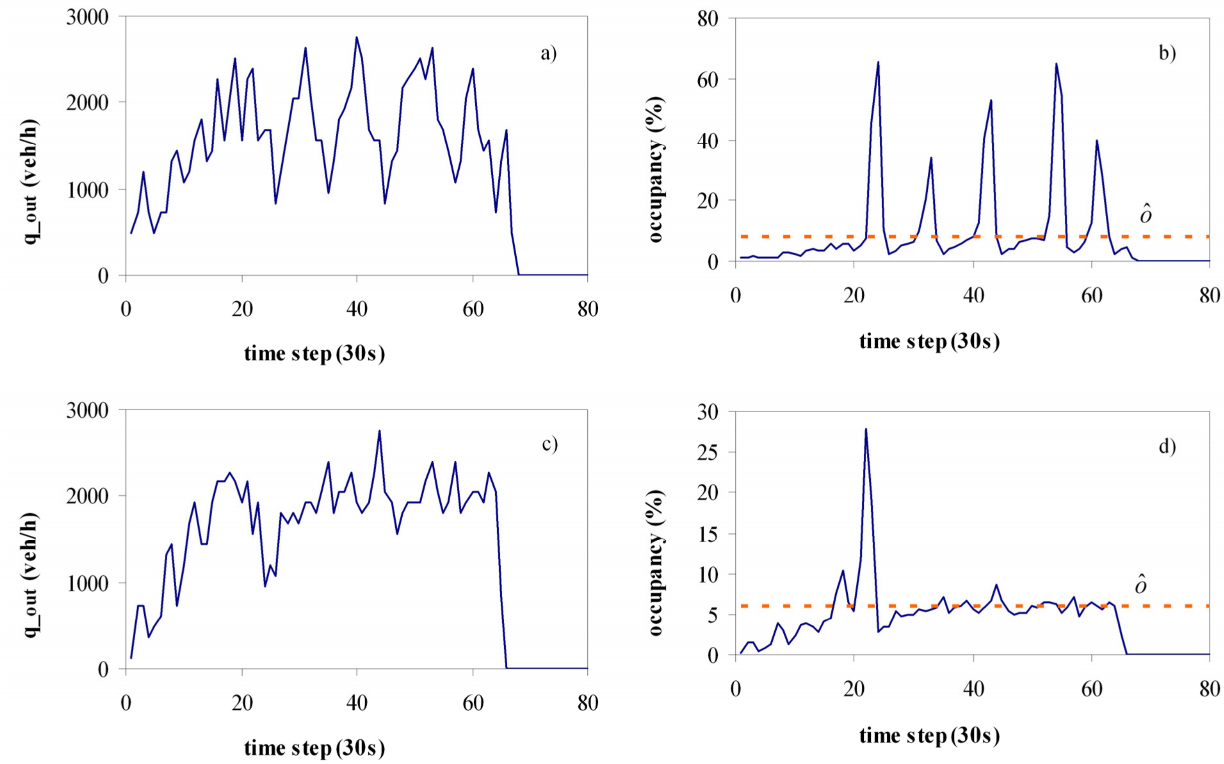

FIGURE 7 Outflow q_{out} and occupancy o for merging traffic control (K_R = 100 veh/h/%): (a) and (b) with $\hat{o}$ = 8 %; (c) and (d) with $\hat{o}$ = 6 %.

undershootings, during which the outflow is seriously reduced. Between the spikes, there are subperiods of proper regulation, with $o(k) \approx \hat{o}$ and $q_{out} \approx q_{cap} \approx 2300$ veh/h.

Figure 6c displays the corresponding flow values $q(k)$ ordered by the feedback regulator (Equation 1) as well as the actual inflow values q_{in} occurring via operation of the traffic lights. As mentioned earlier, for k < 18 (and k > 62) the control input saturates (i.e., $q(k) \equiv q_{max}$) because $o < \hat{o}$ over several time steps, while the actual inflow q_{in} is essentially uncontrolled. At around k = 18, o exceeds $\hat{o}$, and $q(k)$ starts decreasing to address the initial overshooting of *N*. During the regular control period $k \in [25, 60]$, $q(k)$ is varied appropriately via Equation 1 so as to keep o near its set value $\hat{o}$. Figure 6c also shows that the actual entering flow q_{in} created via the signal settings according to Equation 2, deviates from the flow q ordered by the feedback algorithm. Nevertheless, the regulator maintains o equal to $\hat{o}$ in average (except for the occupancy spikes) thanks to its integral-feedback structure as mentioned earlier, see (*3*).

It is interesting to note that the manifest probability of occurrence of the spikes increases in our simulations with increasing $\hat{o}$ beyond 7%, see, e.g., Figures 7a and b displaying the outflow q_{out} and occupancy o, respectively, for a simulation run with $\hat{o} = 8\%$ (and $K_R = 100$), leading to AVD = 175 s/veh/km; it may be seen that the occupancy spikes are more frequent than in the case $\hat{o} = 7\%$ of Figure 6b. In contrast, for $\hat{o} = 6\%$ there are virtually no spikes (other than the initial overshooting) observed in the corresponding 10 simulation replications, i.e. the occupancy is maintained around 6% while $q_{out} \approx 2100$ veh/h, i.e. lower than capacity. However, the average outflow for $\hat{o} = 7\%$ is apparently higher than $q_{out} \approx 2100$ veh/h of the case $\hat{o} = 6\%$,

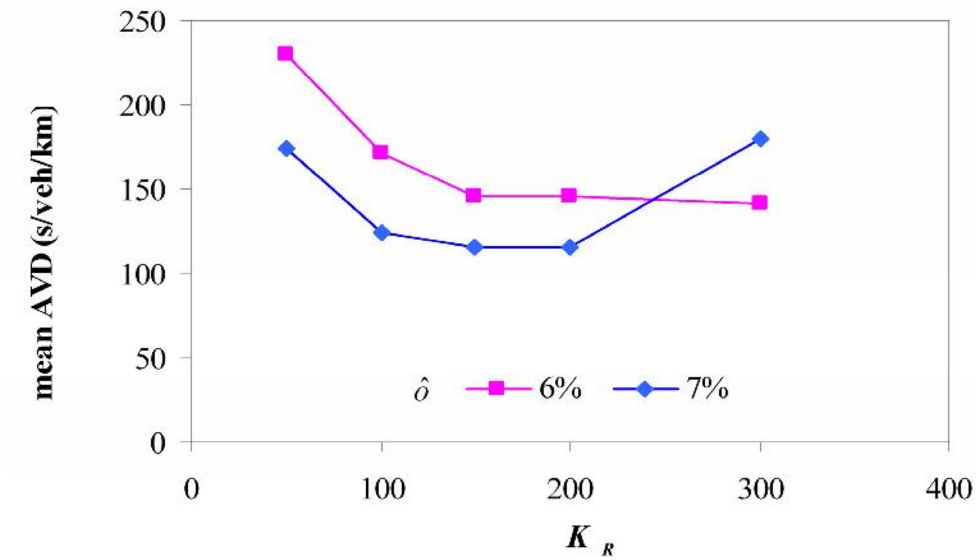

FIGURE 8 Mean AVD versus K_R for $\hat{o}$ = 6 % and $\hat{o}$ = 7 %.

hence the higher mean AVD of the latter in Figure 5. Figures 7c and d display the outflow q_{out} and occupancy o, respectively, for a simulation run with $\hat{o} = 6\%$ (and $K_R = 100$) leading to AVD = 175 s/veh/km.

It is difficult to judge whether the observed occupancy spikes are due to the geometry of the particular merge area or due to the typically limited accuracy of the vehicle-merging behaviour by the microscopic simulator or both. By inspection of the simulator's animation, we suspect that the spikes are mainly due to the simulator's vehicle merging behaviour that leads to virually complete vehicle stops in conflict situations that would probably be much more smooth and swift in real traffic. Related field data are probably the most reliable means to definitely answer this question. In any case, even in the presence of occupancy spikes, the merge area outflow is increased in average with merging traffic control with $\hat{o} = 7\%$, leading to the mentioned mean AVD decrease of 43% against the no-control case, while the formed queue in the control case of Figure 6 ($\hat{o}$=7%) is emptied at around k =60, i.e. 10 steps (5 min) earlier than in the no-control case.

An interesting question is whether a similar increase of efficiency could be achieved via fixed (rather than real-time) traffic lights operation, so as to have a fixed merge area entering flow $\hat{q}_{in}$ near q_{cap} as proposed in (*2*). The potential problem of such an approach is that, if $\hat{q}_{in}$ is set close to q_{cap} (to maximize efficiency), then occasional (stochastic) merging conflicts may reduce the outflow q_{out} temporarily thus increasing N and o; in absence of real-time control, the increased N cannot be controlled, and the formed congestion cannot be dissolved since $\hat{q}_{in} > q_{out}$. On the other hand, if $\hat{q}_{in}$ is set smaller than q_{cap} (to minimize the probability of serious merging conflicts and subsequent congestion), then the resulting outflow q_{out} will be accordingly smaller than q_{cap}, which leads to lower efficiency.

The reported merging traffic control simulation results were produced with a value $K_R = 100$ veh/h/% in Equation 1. It is important to investigate the sensitivity of the control results with respect to the value of K_R, since high sensitivity may imply a high effort of fine-tuning in potential field applications. Figure 8 displays the mean AVD values resulting from merging traffic control with $\hat{o}$ equal to 6% and 7%, against K_R within the range [50, 300]. Note that each point in Figure 8 corresponds to a specific couple of utilized K_R, $\hat{o}$ values, and that 10 simulation replications were carried out for each such couple.

It may be seen in Figure 8 that the mean AVD is improved for $K_R > 100$ in the case $\hat{o} = 6\%$, due to better handling of the initial overshooting as explained earlier. For $\hat{o} = 7\%$, best results are obtained in the range $K_R \in [100, 200]$; for $K_R < 100$, the control performance deteriorates due to slower handling of the occurring spikes by the regulator; for $K_R > 200$, the control performance deteriorates due to the regulator's overreaction to the occurring occupancy spikes.

In conclusion, there is a broad range of K_R values, for which the merging traffic control behavior is sufficiently efficient, and hence the need for fine-tuning K_R in potential field applications is expected to be limited. Field trials would provide more evidence about the actual occupancy behavior under control and, most importantly, about the achievable level of benefits via merging traffic control.

CONCLUSIONS

A simple control concept was developed for real-time merging traffic control in work zone freeway infrastructures where vehicles entering the work zone are merging from a higher to a lower number of lanes. The control concept employs the well-known local ramp metering strategy ALINEA and aims at throughput maximization (or, equivalently, delay minimization) in the corresponding work zone facilities. The concept is demonstrated via microscopic simulation for a particular hypothetical work zone, to lead to sensible improvements in terms of throughput and delays while the necessary fine-tuning effort in potential field application is expected to be limited due to low sensitivity. Some particular phenomena (occupancy spikes) encountered in the simulation investigations are expected to have a minor significance in potential field applications.

REFERENCES

1. FHWA. *Developing and Implementing Transportation Management Plans for Work Zones*. Report of the Federal Highway Administration, U.S. Department of Transportation, 2005.
2. Wei, H. and M. Pavithran. Concept of Dynamic Merge Metering Approach for Work Zone Traffic Control. *Preprints 11th IFAC Symposium on Control in Transportation Systems*, Delft, The Netherlands, 2006, pp. 374-379.
3. Papageorgiou, M., H. Hadj-Salem, and J.-M. Blosseville. ALINEA: A Local Feedback Control Law for On-Ramp Metering. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1320, TRB, National Research Council, Washington, D.C., 1991, pp. 58-64.
4. Papageorgiou, M., I. Papamichail, A. D. Spiliopoulou, and A. F. Lentzakis. Real-Time Merging Traffic Control with Applications to Toll Plaza and Work Zone Management. *Transportation Research Part C*, 2008, in press.
5. Kondyli, A., A. Duret, and L. Elefteriadou. Evaluation of CORSIM and AIMSUN for Freeway Merging Segments Under Breakdown Conditions. Presented at the *86th Annual Meeting of the Transportation Research Board*, Washington, D.C., January, 2007.

6. Lorenz, M., and L. Elefteriadou. Defining Highway Capacity as a Function of the Breakdown Probability. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1776, TRB, National Research Council, Washington, D.C., 2001, pp. 43–51.
7. Cassidy, M. J., and J. Rudjanakanoknad. Increasing the Capacity of an Isolated Merge by Metering its On-Ramp. *Transportation Research Part B*, Vol. 39, 2005, pp. 896–913.
8. Keen, K. G., M. J. Schoffield, and G. C. Hay. Ramp Metering Access Control on M6 Freeway. *Proc. 2nd IEE International Conference on Road Traffic Control*, London, UK, 1986.
9. Papageorgiou, M., E. Kosmatopoulos, M. Protopapas, and I. Papamichail. *Evaluation of the Effects of Variable Speed Limits on Freeway Traffic using M42 Traffic Data*. Internal Report 2006–25, Dynamic Systems and Simulation Laboratory, Technical University of Crete, Chania, Greece, 2006.
10. Vigos, G., M. Papageorgiou, and Y. Wang. Real-Time Estimation of Vehicle-Count within Signalized Links. *Transportation Research Part C,* Vol. 16, 2008, in press.
11. Kosmatopoulos, E. B., and M. Papageorgiou. Stability Analysis of the Freeway Ramp Metering Control Strategy ALINEA. *CD-ROM*, *11th IEEE Mediterranean Conference on Control & Automation*, Rhodes, Greece, 2003.
12. Smaragdis, E., M. Papageorgiou, and E. Kosmatopoulos. A Flow-Maximizing Adaptive Local Ramp Metering Strategy. *Transportation Research Part B*, Vol. 38, 2004, pp. 251-270.
13. Papageorgiou, M. and I. Papamichail. Overview of traffic signal operation policies for ramp metering. *87th Annual Meeting of the Transportation Research Record*, Washington, D.C., 2008, paper 08-0777.