Limitations of Simultaneous Gap Out Logic.

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Abstract

Current practice of specifying simultaneous gap out logic places constraints on the signal controller logic that under high traffic flow conditions cannot be achieved and often results in degraded signal efficiency and dilemma zone protection. This study documents this phenomenon using set back detectors at an instrumented intersection in Noblesville, IN, and characterizes the problem of dilemma zone protection as traffic volume dependent that should be carefully considered before applying the simultaneous gap out logic. Implementation of the simultaneous gap out logic led to max out ranging from 3.5 to 40 % of cycles per hour during the peak traffic flow periods and around 200 dilemma zone incursions per day. Results also indicated that the simultaneous gap out logic performs inefficiently and unsafely under high volume conditions whereas under low volume condition it has satisfactory performance. Analysis suggests an upper bound on potential savings of about 400 seconds of green time per day and a 25% reduction in dilemma zone incursions.
INTRODUCTION
Intersection crashes constitute a significant portion of total fatalities nationwide; they account for an average of 9,000 fatalities and 1.5 million injuries annually. Red light running (RLR) is a major cause of fatal and injury-related crashes. Also, motorists are more likely to be injured in such crashes. The National Highway Traffic Safety Administration reported that in 2002 there were 921 fatalities and 178,000 injuries resulting from 207,000 crashes attributable to motorists running red lights at signalized intersections. A survey conducted by the U.S. Department of Transportation and the American Trauma Society indicates that 63 percent of Americans witness a RLR incident more than once a week and one in three Americans knows someone who has been injured or killed because of a red-light runner.

Rural high-speed isolated intersections are more susceptible to such crashes. Drivers travel at high speeds at such intersections with a high expectancy of proceeding through them without stopping. This expectancy is violated under dilemma zone incursions, leading to elevated risk of crashes. The most commonly implemented strategy to eliminate this problem is enabling simultaneous gap out logic.

Simultaneous gap out logic is adopted at isolated intersections to provide dilemma zone protection for the drivers on the primary street. This logic is widely believed to always provide dilemma zone protection at an intersection. Despite the widespread application of this logic there has been little, if any, literature which reports the limitations of simultaneous gap out logic in providing dilemma zone protection. This paper provides a framework to evaluate the real-time performance of the simultaneous gap out logic and highlights its limitations using an instrumented intersection at Noblesville, IN.

PROBLEM DESCRIPTION
Dilemma Zone
The dilemma zone constitutes the area on the roadway where the driver is indecisive about whether to stop or to go on the onset of yellow interval (2). Figure 1 shows this concept graphically. Driver 1 in the “Can Go” zone can safely cross the intersection while staying within the speed limit. Driver 3 in “Can Stop” can come to a safe stop before the stop bar with a comfortable deceleration. Driver 2 in the “Dilemma Zone” can neither cross the intersection before the onset of red if he stays within speed limit nor can stop the vehicle by applying a comfortable deceleration. Sheffi and Mahmassani (3) identify the dilemma as the drivers’ decision to proceed through the intersection or to stop when the signal indication changes from green to amber. The concept of a dilemma zone appeared in studies by Gazis et al. (4), Olson and Rothery (5), Crawford (6) and Herman (7). Sheffi and Mahmassani (3) further defined it as that zone within which the driver could neither come to a stop nor proceed through the intersection before the end of the amber phase. Zegeer (8) proposed a probabilistic approach by defining a dilemma zone as the road segment where more than 10% and less than 90% of the drivers would choose to stop. Sheffi and Mahmassani (3) developed dilemma zone curves of ‘percent drivers stopping’ versus ‘distance from stop bar’
at the instant when the signal indication changes from green to amber. Dilemma zone is also referred to as the “option zone” or the “zone of indecision” \( (9) \).

Occurrences of a dilemma zone incursion (presence of driver/drivers in the dilemma zone) elevate the risk of crashes. Dilemma zone incursions have also been identified as major causes of red light running and rear end collisions. Dilemma zone protection is provided to minimize, and if possible eliminate, the occurrences of dilemma zone incursions. This is usually accomplished by placing an advance vehicle detector just beyond the start of dilemma zone (as shown in Figure 1). This detector detects a vehicle and extends the green sufficiently to allow it travel past the dilemma zone to the “Can Go” zone. This measure is referred to as green extension system. A “before-and-after” evaluation, conducted by Zegeer and Deen \( (10) \), of extension system on three intersections in Kentucky to determine their effect on crashes showed a 54 percent reduction in accidents per year at the three sites combined. The duration of the before-period was 8.5 years and the duration of the after-period was 3.7 years. There were 70 accidents in the before-period and 14 accidents in the after-period.

The safety benefits are negated in cases where the phase reaches its maximum green time and arbitrarily terminates (max out). The green extension system usually uses simultaneous gap out logic to pool the through lanes of high speed movement. The green extension logic works well at low volume conditions. However, the frequency of max out increases with the increase in traffic volume thus jeopardizing both safety and efficiency of operations at the intersection. Enhanced systems like the TTI truck priority system \( (11) \), intelligent detection-control system \( (12) \) etc. promising improved dilemma zone protection have also been developed but are still not widely used because of high technology cost. Some methodologies \( (13,14) \) have been developed that dynamically vary the clearance intervals (yellow clearance and all red) to minimize dilemma zone incursions. These methodologies have not been widely implemented or tested. They can be used as complementary to the methodologies which extend the green interval for eliminating dilemma zone incursions. This paper focuses on the evaluation of simultaneous gap out logic which is the most commonly used feature, available in almost all the controllers, for dilemma zone protection. The concept of simultaneous gap out logic is explained hereafter.

**Simultaneous gap out logic**

In actuated control, phases 2 and 6 (main street through phases) are most often linked for gap out purposes. This imposes an additional constraint on the control system. The constraint requires that when crossing the barrier, phases 2 and 6 must gap out together in order to terminate the green interval. In the absence of simultaneous gap out logic, if phase 2 gaps out prior to phase 6 both the phases go to clearance as soon as a gap is found in phase 6 regardless of any new call placed on phase 2. With simultaneous gap out enabled the new call will extend phase 2 even though it would have already gapped out. Here, phase 2 and phase 6 need to gap out simultaneously to end the phases. Hence, the simultaneous gap out logic inherently increases the likelihood of max out scenarios.

Figure 2 illustrates the principle of simultaneous gap out logic for a hypothetical intersection. Figure 2a shows the snapshot of the hypothetical intersection with position of cars at time zero. Figure 2b plots the time at which the advance detectors of north bound and
south bound are actuated. The third plot from top in Figure 2b shows the actuations seen by the controller if the simultaneous gap out logic was implemented. An extension time of 4 sec is assumed (with each actuation, green is extended by 4 seconds). The max out time is assumed to be 18 seconds. There are three vehicles in north bound direction passing the advance detector at time 1 sec, 12 sec and 16 sec, respectively, and three vehicles in south bound direction which are detected by the advance detector at time 3 sec, 5.5 sec and 9 sec, respectively. Suppose north bound direction is serviced by phase 2 and phase 6 services south bound direction. If the simultaneous gap out logic is not implemented phase 2 will gap out at 5 sec and phase 6 gaps out at 13 sec, thus phases 2 and 6 enter the clearance interval at 13 seconds. However, as can be observed from the Figure 2, one vehicle at 12 seconds will be present in the dilemma zone. If instead, the simultaneous gap out logic were implemented, phases 2 and 6 keep extending until 18 seconds when the phase goes to the clearance interval due to max out. However, this also leads to one dilemma zone incursion. There would be no dilemma zone incursion if the max time were greater than 20 seconds. But with a max out time setting of 18 sec the simultaneous gap out logic drags the cycle length without providing any safety benefits.

The above example illustrates that simultaneous gap out logic can be problematic in cases of medium to high volumes. Under such scenarios it will reduce the efficiency of the intersection without any dilemma zone protection when the phases max out. The maxing out of phases leads to increase in cycle lengths. The increase in cycle length results in increased delay on the intersection thereby increasing the travel time and vehicle operating costs. HCM (15) delay equations shown below relate the delay at signalized intersection with the cycle length.

\[
d = d_1(PF) + d_2 + d_3
\]
\[
d_1 = \frac{0.5C(1 - \frac{g}{C})^2}{1 - \min(1, X)\frac{g}{C}}
\]
\[
d_2 = 900T\left( (X - 1) + \sqrt{(X - 1)^2 + \frac{8kIX}{cT}} \right)
\]

where:
- \(d\) = control delay to the through movement, s/veh;
- \(d1\) = uniform delay, s/veh;
- \(d2\) = incremental delay, s/veh;
- \(d3\) = initial queue delay, s/veh;
- \(PF\) = progression adjustment factor;
- \(X\) = volume to capacity ratio for the through lane group;
- \(C\) = cycle length, s;
- \(c\) = capacity of the lane group, veh/h;
- \(g\) = effective green time for the through lane group, s;
- \(T\) = duration of analysis period, h;
- \(k\) = incremental delay adjustment for actuated control; and
I = incremental delay adjustment for filtering by upstream signal.

This paper provides insights for developing adaptive strategies in the future that consider the inverse relation between dilemma zone protection and efficiency at moderate and high traffic volumes.

DATA COLLECTION AND PROCESSING

Figure 3 shows the data collection site located at the signalized intersection of SR 37 and SR 38 in Noblesville IN. This is a heavily instrumented intersection with capabilities for collecting detector actuations, signal states and simultaneous video recording of the existing traffic conditions. The north bound and south bound approaches are the high speed approaches with a posted speed limit of 55 mph (88 Kmph). These are the approaches of interest.

Detectors NA8, NB8, SA5 and SB5 were used for data collection. These are the set of advance detectors located 405 ft away from the stop bar. Phase data was also obtained for phases 2 and 6. Table 1 shows an example data log file. The occurrences of events are recorded in the data log file in the order of which they occur. It can be seen from Table 1 that at 12:00:05.046 am phase 6 red turned off (state = 0), that is phase 6 turned green. Similarly there was actuation (state = 1) of detector NB8 (shown in Figure 3) at 12:00:18.196 am and it turned off (state = 0) at 12:00:18.396 am. The detector actuations and phase changes can be recorded in a data file with a precision of 1/1000 of a second and is accurate to within approximately 1/100 of a second. Data was collected for the twenty-four hour period on Tuesday between 05/31/05 12:00 A.M. to 06/01/05 12:00 A.M. Matlab (16) code was used for data processing.

Two signal logic approaches were evaluated on a cycle by cycle basis. They are labeled the traditional approach and the ideal approach. A maximum green time of 40 seconds and green extension time of 4 seconds were used for the evaluation. The green extension of 4 seconds was calculated to provide dilemma zone protection for vehicle within the speed range of 35 to 55 mph. The traditional approach uses the standard simultaneous gap out logic. The ideal approach assumes perfect a priori knowledge of the future actuation and tries to avoid max out by reducing the number of detectors (lanes) included in the simultaneous gap out logic. It provides a benchmark for the upper limit on the potential savings obtainable compared to the traditional approach. Figure 4 compares the traditional and ideal approaches. The ideal approach starts with traditional simultaneous gap out logic at the start of green. At the end of a pre-specified green duration the simultaneous gap out strategy constraints are relaxed. Instead, the maximum numbers of lanes that can avoid max out are included in the simultaneous gap out logic. In on-going research, we are analyzing methods to determine the “optimal” pre-specified green duration and the maximum number of lanes for the simultaneous gap out logic consider the inverse relation between dilemma zone protection and efficiency.
Traditional Approach
The durations of green for phases 2 and 6 were calculated using the simultaneous gap out logic. In the case of max times forcing a phase to terminate, the total number of dilemma zone incursions on all the four lanes were reported. The numbers of dilemma zone incursions were determined by counting the number of vehicles which cross the advance detectors within last of 4 seconds before ending of through green phase.

Ideal Approach
The ideal approach uses prior knowledge of the future to select a strategy which will, on average, provide maximum dilemma zone protection without triggering max out. For example, if the strategy using all 4 lanes in the simultaneous gap out logic leads to max out, the ideal approach will test if a subset of any 3 lanes can be used in the simultaneous gap out logic and avoid max out. It will use the 3 lanes which provide least extension to the phases. However, there are situations when the queue does not clear in at least one of the 4 lanes, thus the minimum green cannot be served and the phase terminates through max out. These situations occur at very high volumes and even the ideal approach will provide no benefits in such instances.

In the field, stochastic control logic would be implemented by determining when a phase is likely to max out; then the maximum number of lanes which would avoid the max out would be included. The lanes are chosen to minimize the extension of green phase.

A separate study was performed to measure the variation of speed over the course of day. This study was performed to evaluate the effects of congestion reducing the speed and potentially negating the need for dilemma zone protection. Figure 5 shows the daily variation of average speed, 85 percentile and 15 percentile speed during the course of a day. The data was collected on Friday 10/21/05. As can be seen from Figure 5, average speed has a modest drop. However, the 85% speed remains virtually unchanged. This 85% speed corresponds to vehicle at the back of the queue most likely to encounter dilemma zone. Hence, the dilemma zone boundaries do not change significantly during peak hour congestion.

RESULTS
Figures 6 shows the percentage of cycles maxing out per hour and the number of dilemma zone incursions under the traditional approach. It indicates that the simultaneous gap out logic works well during the night when traffic volumes are low. However, during the morning, noon, and evening peaks, the percentage of max outs can be substantial, and range from 3.5% to as high as 40%. High percentages of max out are usually observed during the evening peak. The 40% max out suggests that nearly half of the cycles in that hour were forced to max out. The higher frequency of max outs during the peak periods have a negative impact on the operational efficiency during those periods as cycle length extensions may lead to excessive delays on the cross streets. Further, as described earlier, max out does not necessarily ensure dilemma zone protection.

In the dilemma zone incursion plot of Figure 6, the bars represent the number of incursions occurring per hour and the solid line denotes the cumulative sum of incursions up to that hour. The figure indicates 213 incursions occurred on the day the data was collected,
with the highest hourly rate of incursions of 60 vehicles/hr. These numbers are highly significant from a safety standpoint as they indicate the number of drivers exposed to higher risk of crashes per day. These figures are substantial when aggregated across all high speed rural intersections in the country as they indicate that a significant proportion of the total driver population faces high crash risk per day.

Further, Figure 6 suggests a correlation between cycles maxing out and the number of dilemma zone incursions. This suggests the potential for developing “optimal” signal control strategies that simultaneously reduce the number of max outs and the number of dilemma zone incursions. However, this trend is not universal and indicates the need for stochastic models that explicitly account for the randomness and inverse relationship of these two objectives.

Figure 7 plots the strategies applied in the ideal approach. In many instances, dropping just one of the four lanes (identified by points “a” in Figure 7) linked to the simultaneous gap out logic can prevent the max out occurrence. However, the figure also illustrates that there are cases (denoted by points “b” in the figure) when dropping all 4 lanes does not prevent max out because the queues cannot be cleared owing to the heavy traffic. The insights from this figure further reinforce the need for stochastic models that can adapt to real-time data and generate “optimal” strategies to terminate green.

Figure 8 shows potential savings in reduction in cycle length as well as reduction in dilemma zone incursions that can be achieved by applying an inexpensive and simple strategy of using a subset from among the 4 lanes linked to the simultaneous gap out logic. For academic purposes, to show the potential benefits that can be achieved, perfect a priori knowledge of the future was assumed. The gross cycle length reductions obtained for ideal approach were adjusted for additional time required to serve the excess vehicles (served by traditional approach) which join the queue due to early return to green in ideal approach. In our study example, we note that around 400 seconds of cycle length can be saved. These savings will occur during peak periods of the day, when the intersection has very little excess capacity. These savings correspond to increased throughput of approximately 800 vehicles per day during the peak periods (assuming the 4 lanes can be serviced from during the saved green time). Reduced cycle lengths will also lead to reduced delays and queue lengths on the secondary streets, thereby reducing driver frustration on these streets and improving public perception of the efficiency of these signal systems. Figure 8 further illustrates that a reduction of approximately 50 dilemma zone incursions per day could be potentially saved by using such logic. This corresponds to about 25% reduction in dilemma zone incursions per day for this case study. It should also be noted that during certain periods the dilemma zone incursions might be higher under the ideal approach, but on an average, they will be less than under the traditional approach. As stated earlier, this suggests the need for developing stochastic models to more robustly enhance the efficiency and safety objectives.

CONCLUSIONS AND RECOMMENDATIONS

Simultaneous gap out logic is widely used in the field with the intent of enhancing safety at the expense of efficiency. The motivation of this paper is to initiate a discussion on the performance of simultaneous gap out logic. The study results suggest that the dilemma zone performance deteriorates steeply during peak periods. An important insight is that both the
frequency of max outs and dilemma zone interactions increase, on average, during the peak period. So, there exists the potential for strategies which can improve on one or both of the primary objectives. As a preliminary step, we benchmark the performance of a simple and inexpensive strategy to enhance the performance of simultaneous gap out logic. On-going research seeks to develop stochastic models which adapt to the field data and trade-off the efficiency and safety objectives to generate non-dominated solutions to this problem.

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<table>
<thead>
<tr>
<th>Detector Title</th>
<th>Time</th>
<th>State</th>
<th>Description</th>
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<tr>
<td>PH 6</td>
<td>5/31/2005 12:00:05.046 AM</td>
<td>0</td>
<td>Phase 6 turns green</td>
</tr>
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<td>1</td>
<td>Detector NB8 turns on</td>
</tr>
<tr>
<td>NB8</td>
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<td>0</td>
<td>Detector NB8 turns off</td>
</tr>
<tr>
<td>PH2</td>
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<td>Phase 2 turns red</td>
</tr>
<tr>
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<td>Phase 6 turns red</td>
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<td>5/31/2005 12:00:44.593 AM</td>
<td>1</td>
<td>Detector NB8 turns on</td>
</tr>
</tbody>
</table>
FIGURE 1 The dilemma zone.
FIGURE 2 Illustration of simultaneous gap out logic.
FIGURE 3 Data collection site at Noblesville, IN.
All detectors should simultaneously gap to terminate earlier than max green

**FIGURE 4** Description of the traditional and ideal approaches.
a) Speed variation during green in NA lane.

FIGURE 5 Daily variation in speed in northbound direction at Noblesville, IN.

b) Speed variation during green in NB lane.
FIGURE 6 Performance of traditional approach on 5/31/2005.
Subset of All Detectors Used in Ideal Approach

FIGURE 7 Strategy applied on 05/31/2005 assuming perfect knowledge.
FIGURE 8 Potential savings by applying ideal approach on 05/31/2005.