Final Report

DILEMMA ZONE PROTECTION AND SIGNAL COORDINATION AT CLOSELY-SPACED HIGH-SPEED INTERSECTIONS

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Prepared in cooperation with
The Ohio Department of Transportation
and
The U.S. Department of Transportation, Federal Highway Administration

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16. Abstract

A feasibility study of dilemma zone problems, performed by collecting and analyzing traffic flow data at a high-speed signalized intersection, showed that the maximum green extension or cutback needed to get a vehicle out of the dilemma zone is generally no more than 2 seconds. If we scan all vehicles on a link just a few seconds before the beginning of a yellow interval, we may be able to extend or cutback the green interval so that the vehicles can avoid the dilemma zone. For each vehicle approaching an intersection on the link that is about to turn yellow, there is a time interval such that (a) the vehicle will be in dilemma zone without green extension (or cutback) or (b) it will be in dilemma zone when there is T seconds of extension (or cutback). So the task is to find the smallest nonnegative integer T that is not in any of these time intervals and extend (or cutback) the current interval by T seconds. This T can always be found and assuming there are no other restrictions, dilemma zones can be avoided and the extension (or cutback) is done at most once for each green interval. Our simulation study, performed by modifying the source codes of NETSIM, showed that the signal timing generated by a bandwidth maximization program (PASSER-II) resulted in lower number of vehicles in dilemma zone than that generated by a delay minimization program (TRANSYT-7F). Additionally, the signal timing generated by the combination of the two programs, that is, by minimizing delay within the constraint of bandwidth maximization, resulted in even lower number of vehicles in dilemma zone than those generated by each program alone. The technique developed in this study can be implemented if the speeds and positions of all vehicles on the roadway can be recorded at small time intervals (e.g. 1 sec). Recommendations are made for implementing and testing the developed technique.

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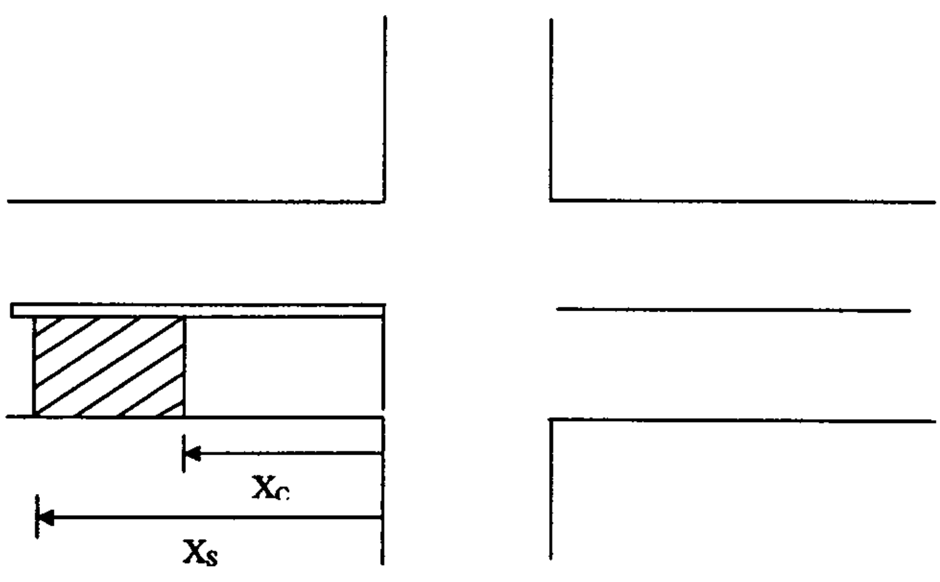
DILEMMA ZONE PROTECTION AND SIGNAL COORDINATION AT CLOSELY-SPACED HIGH-SPEED INTERSECTIONS

1 INTRODUCTION

A high accident potential exists at high-speed signalized intersections where an area close to an intersection, called a dilemma zone (also known as decision zone), often poses a problem to a driver in stopping safely during the yellow interval or in proceeding through the intersection before the beginning of red interval. The driver is exposed to a potentially hazardous situation in which a rear end accident may occur if he stops abruptly during the yellow period or an angle accident if he attempts to cross the intersection at the onset of the red interval.

A vehicle should be able to safely come to a stop during the signal change interval, and it should also be able to safely clear the intersection during the same interval. In Figure 1, the stopping distance is referred to as X_s and the clearing distance is referred to as X_c. If the vehicle is farther than X_s or closer than $X_{c,}$ it does not experience any dilemma zone. However, if $X_{s\ is}$ greater than X_c and the vehicle is placed between them, a dilemma zone is formed and neither the distance to the intersection is adequate for stopping nor is the yellow interval adequate for clearing the intersection. The stopping sight distances suggested by AASHTO are shown in Table 1. An example of clearing distance for a yellow interval of 4 seconds is shown in Table 2.

Figure 1. Dilemma Zone



X_S = Minimum Stopping Distance
X_C = Maximum Clearing Distance

Table 1 Stopping Sight Distance (Wet Pavements)

Design Speed (mph)	Assumed Speed for Condition (mph)	Brake Reaction		Coeff. of Friction F	Braking Distance on Level (ft)	Stopping Sight Distance	
		Time (sec)	Distance (ft)			Computed (ft)	Rounded for Design (ft)
35	32-35	2.5	117.3-128.3	0.34	100.4-120.1	217.7-248.4	225-250
40	36-40	2.5	132.0-146.7	0.32	135.0-166.7	267.0-313.3	275-325
45	40-45	2.5	146.7-165.0	0.31	172.0-217.7	318.7-382.7	325-400
50	44-50	2.5	161.3-183.3	0.30	215.1-277.8	376.4-461.1	400-475
55	48-55	2.5	176.0-201.7	0.30	256.0-336.1	432.0-537.8	450-550
60	52-60	2.5	190.7-220.0	0.29	310.8-413.8	501.5-633.8	525-650

(Source: AASHTO Book)

Table 2. Clearing Distance for 4 Sec Yellow Interval

Speed (mph)	Clearing Distance (ft) (Computed)
35	204
40	236
45	264
50	292
55	320
60	352

Generally, an intersection approach with vehicular speeds of 35 mph or higher is considered a high-speed approach. When there are several signalized intersections adjacent to each other, it is advantageous to coordinate these signals and provide progressive movements for vehicles in both directions, in order to reduce stops, delay, accidents, vehicle operating costs, and pollutant emissions. When traffic progression is favorable to the subject traffic flow (i.e. most vehicles arrive in the green time), delay will be considerably less than that for random arrivals (i.e. vehicles arrive randomly in both the red and green times).

In a coordinated system, though each intersection can have a different green split, the offsets can be varied between different intersections so the system can provide a green bandwidth favoring one or both directions of traffic. The following three factors affect progression of vehicles on arterial highways or streets:

1. Signal timing;
2. Traffic speed; and

3. Signal spacing.

Among the three factors, the traffic engineer can only exert control over the signal timing, at least in the short term. The traffic speed changes according to the time of the day and motorists are heavily constrained in their choice of speeds during congested traffic conditions. On the other hand, individual vehicular speed seems to vary within a large range during free flow conditions. Signal spacing is fixed for an existing systems.

A coordinated system is designed to provide progression of vehicular movements through the intersections. Several signal timing parameters are important in the design of a coordinated system:

(a) Cycle length;
(b) Offsets;
(c) Green splits; and
(d) Phase sequence.

Drivers seem to vary their speeds at an intersection according to the geometry of the intersection, advance warning signs with flashers (if any), signal indications, and distance to the stop line. Evidence has shown that a large number of drivers on high-speed signalized intersections increase their speeds when they see yellow light or, even worse, go through red fight without stopping. The length of the yellow interval or the timing of the dynamic sign with flashers is typically based on the 85th percentile speed or any variation of the prevailing speed. Neither slow moving vehicles nor other variations in individual speeds are always considered. Hence, a large number of vehicles continue to experience dilemma zone problems at high-speed signalized intersections. The currently available computer programs consider platoon of vehicles for optimization of stop, delay, or green bandwidth. The results including the corresponding measures of effectiveness or performance are given on an aggregate basis. The programs can provide no clue whatsoever if an individual vehicle might experience dilemma zone at the intersections.

A major goal of operating a system of signalized intersections is to provide safe operating conditions without sacrificing efficiency. However, experience has shown that, when adjacent intersections are closely spaced (1000-2000 ft) it is difficult to achieve the twin operational goals of dilemma zone protection and efficiency maximization (signal coordination) at high speed signalized intersections. When faced with the need for both signal coordination and dilemma zone protection, a traffic engineer may be forced to choose one of them, but not both. These problems have become more evident in recent years due to the growth of suburban centers leading to the installation and operation of traffic signals on multi-lane high-speed arterials. It is important, therefore, to develop a procedure which will enable ODOT to both provide dilemma zone protection and maximize signal coordination at closely spaced high-speed signalized intersections.

2 OBJECTIVES

The objectives of this study are to:

(a) Assess the feasibility of reducing dilemma zone problems through adjustments of signal timing parameters without sacrificing the benefits of coordination on closely-spaced (100-2000 ft) high speed ($\geq$35 mph) signalized intersections;

(b) Develop a new technique that can (i) predict vehicles that would experience dilemma zone and (ii) reduce dilemma zone for these vehicles;

(c) Simulate the flow of vehicles in a coordinated signal system and implement the new technique by incorporating it in the simulation software; and

(d) Recommend a procedure for testing and implementation of the technique in an existing arterial corridor.

3 BACKGROUND AND SIGNIFICANCE OF WORK

For over a long time, it has been known that at signalized intersections where approach speeds are 35mph or higher, motorists face a "dilemma" or "decision" problem. Past research works have addressed the problems of determining the signal change interval to find a solution for dilemma zone problems, and thereby reduce accidents. The problem of dilemma zone and the adequacy of signal change interval has been extensively examined ever since it was formulated by Gazis et al (Reference 1) in the early 1960s.

In the past, several methods have been used to address the dilemma zone problem. These include:

(1) <u>Adjustment of phase-change interval:</u>

The following equation may be used to calculate the duration of the yellow interval (Reference 2):

$$y = t + V/(2a) \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where,

y = length of the yellow interval, seconds
t = perception-reaction time (usually 1 sec)
V = approach speed, ft/s
a = deceleration rate, ft/s/s

If it is desired to provide an additional all-red clearance at the intersection, it may be calculated as follows:

$$r = (W + L)/V \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where,

r = length of all-red clearance, seconds
W = width of intersection, ft
L = length of vehicle, ft
V = approach speed, ft/s

Hence, the total phase-change period is the sum of equations (1) and (2). The following table (Reference 2) presents some theoretical minimum clearance intervals for various approach speeds and cross street widths.

Table 3. Theoretical Minimum Clearance Intervals

Approach Speed (mph)	Yellow Interval (sec)	Total Clearance Interval (yellow plus all-red clearance for crossing street widths, feet)				
		30	50	70	90	110
20	3.0	4.2	4.9	5.5	6.2	6.9
25	3.0	4.2	4.7	5.3	5.8	6.4
30	3.2	4.3	4.8	5.2	5.7	6.2
35	3.6	4.5	4.9	5.3	5.7	6.1
40	3.9	4.8	5.1	5.5	5.8	6.1
45	4.5	5.1	5.4	5.7	6.0	6.3
50	4.7	5.3	5.6	5.9	6.2	6.4
55	5.0	5.7	5.9	6.2	6.4	6.7

t = 1 sec; a 10 ft/s/s; and L= 20 ft

(2) Vehicle detection upstream of the intersection:

Detector location and configuration is dependent on:

- Type and capability of controller
- Control mode
- Traffic variable to be measured
- Geometry of the intersection and approaches
- Traffic flow characteristics (e.g. volume, speed, etc.)

Either a pretimed or a traffic-actuated controller can be used at a signalized intersection. A pretimed controller operates with a fixed cycle length and phase lengths according to a predetermined schedule. A traffic-actuated controller may be operated on several ways according to the type of equipment available and the operational requirements such as (a) a full-actuated control, (b) a semi-actuated control, or (c) a volume-density control. Each type of control has its own advantages and disadvantages.

Various types of detector configurations are used to minimize the untimely display of yellow interval that might cause dilemma zone problem In general, some type of multiple loop configurations (or "stretch" detectors) are used in advance of high speed signalized intersections. A common configuration used at high speed signalized intersection is the EC-DC (extended call-delayed call) design.

Earlier studies on the effect of green extensions to reduce accidents were performed by Zegeer (Reference 3). Parsonson (References 4 and 5) established dilemma zone boundaries as being within the range of 10% to 90% probability of stopping from various speeds. Table 4 shows the boundaries of dilemma zone. Parsonson also studied the use green extension systems and provided taxonomy of detector-controller configurations as a solution for dilemma zone problems.

Table 4 Dilemma Zone Boundaries

Approach Speed (mph)	Distance from Intersection in ft Probabilities of Stopping 10%	 90%
35	102	254
40	122	284
45	152	327
20	172	353
55	234	386

(3) <u>Dynamic Advance Warning Signs With Flashers</u>:

Detector strategies may vary with or without the use of passive or dynamic warning signs. There is a wide spread feeling that intelligent detectorization can at least reduce the need for advance warning signs. The most commonly used dynamic sign used by the Ohio Department of Transportation (ODOT) is the "Prepare to Stop When Flashing" (PTSWF) sign. As shown in Figure 2, the sign has two flashers that begin to flash a few seconds before the onset of the yellow interval and continue to flash until the end of the red interval. In most case, the detectors are effectively inactive during the flashing of the PTSWF sign.

ODOT also uses a Continuously Flashing Symbolic Signal Ahead (CFSSA) sign (Figure 2) at high-speed signalized intersections. The CFSSA sign, as the name suggests, has green, red, and yellow circles and flashers that flash all the time. The flashers are not connected to the signal controller and hence, detectors, if any, have no effect on the flashing of the CFSSA sign.

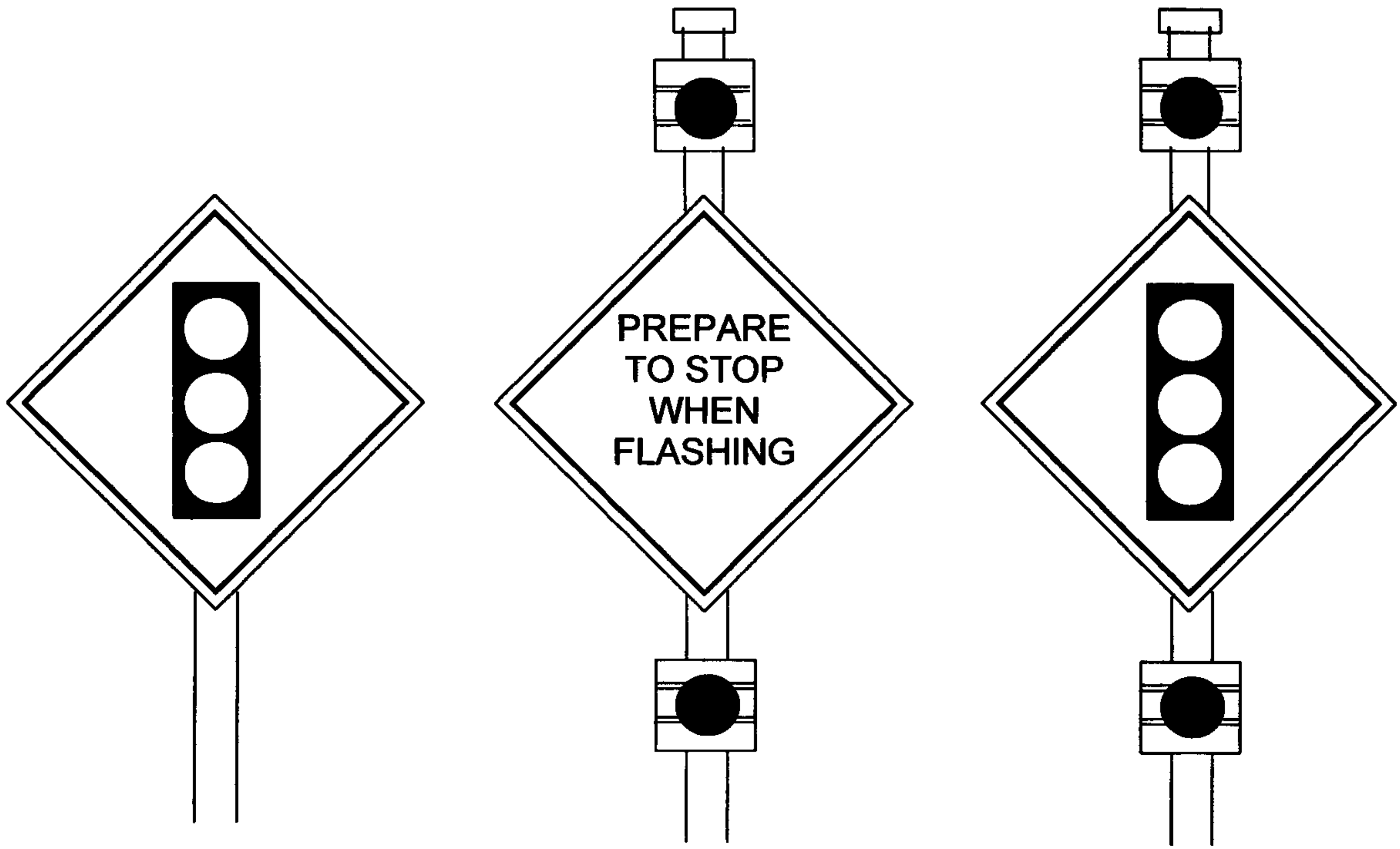
An additional sign that has been used by ODOT is the Flashing Symbolic Signal Ahead (FSSA) sign, which is similar to the PTSWF sign except that the texts are replaced by the green, yellow, and red circles. The flashers operate in the same manner as the PTSWF sign.

A study by the University of Cincinnati (References 6,7,8,9) examined the effectiveness of the PTSWF, FSSA, CFSSA signs at tangent and curved approaches of rural and suburban high-speed signalized intersections. The recommendations of the study are listed below:

(a) The use of the PTSWF sign at tangent approach of high-speed signalized intersections is discouraged. The ODOT may consider reviewing speed, vehicular conflict, and accident data at existing high-speed signalized intersections with tangent approach for possible switching from PTSWF to CFSSA sign.

(b) At any potential location for an advance warning sign with flashers, the CFSSA sign should be considered for selection prior to the PTSWF sign.

Figure 2 Advance Warning Signs



(a) PSSA sign (b) PTSWF sign (C) CFSSA & FSSA signs

(c) The PTSWF sign is preferable to the FSSA sign in Ohio. The FSSA sign should not be used as a replacement for the PTSWF sign.

In summary, previous studies have mostly concentrated on determining the extent of dilemma zone, the driver behavior during the signal change interval (green to yellow), the placement of detectors to detect a vehicle in the dilernma zone, and the use of dynamic warning signs with flashers. Most of these works were done from the point of view of an isolated intersection. However, not all intersections are isolated. On many arterials, the signals are closely spaced (1000-2000 ft). Further research is needed for developing a technique for both alleviating the dilemma zone problem and maintaining the efficiency by coordinating the contiguous intersections to minimize delay.

4 FEASIBILITY STUDY FOR REDUCING DILEMMA ZONE PROBLEMS

A feasibility study for reducing dilemma zone problems was performed by an intensive collection and analysis of traffic flow data on a high-speed intersection approach in the City of Middletown, Ohio. With assistance from the City of Middletown, the intersection of Manchester Road and Marshall Avenue in Middletown, Ohio was selected to collect data on vehicles moving through the intersection during non-peak hours. The 85th percentile speed on the intersection was 55mph, according to the Transportation Administrator of the City of Middletown. The intersection consisted of two through lanes and a left turn lane in the main direction. Traffic volumes during non-peak hours were relatively low, which created potential conditions for vehicles to be caught in a dilemma zone. Video photography was chosen as the technique for simultaneous recording of vehicular movements an a 1362'-long roadway upstream of the intersection. The main advantage of video photography is its capacity to record travel times and vehicle positions accurately and permanently. A total of six Hi-8mm video cameras were installed on utility poles along the roadway including one camera on the signal mast arm, covering a distance of 1362 ft between the stop line and the upstream intersection of Manchester and Cambridge. Each camera could only cover a certain segment of the roadway which was delineated by an orange cone placed on the curbside at each end. Some of the cone positions were common for two cameras. For instance cone #2 was common to cameras 1 and 2, and cone #6 was common to cameras 4 and 5. One camera continuously recorded the signal indications (green, yellow, and red) using a special signal head that was installed at an intersection pole by the City of Middletown. Figure 3 provides a schematic representation of the roadway segment with the camera and cone positions. The vehicular movements and signal indications were simultaneously recorded on videotapes by the six cameras for six weekdays between 9:00am and 4:00 pm for each day. The locations of the cameras were as follows (Figure 4):

Camera 1 - Mast arm	Looking toward east 65' to 148'
Camera 2 - Pole 1	Looking toward west 0' to 95'
Camera 3 - Pole 1	Looking toward east 148' to 228'
Camera 4 – Pole 2	Looking toward east 435' to 677'
Camera 5 – Pole 3	Looking toward west 228' to 435'
Camera 6 – Cambridge Dr	1128' to 1363'

Figure 3 Schematic Diagram of Roadway Upstream of Manchester and Marshall Avenue Intersections

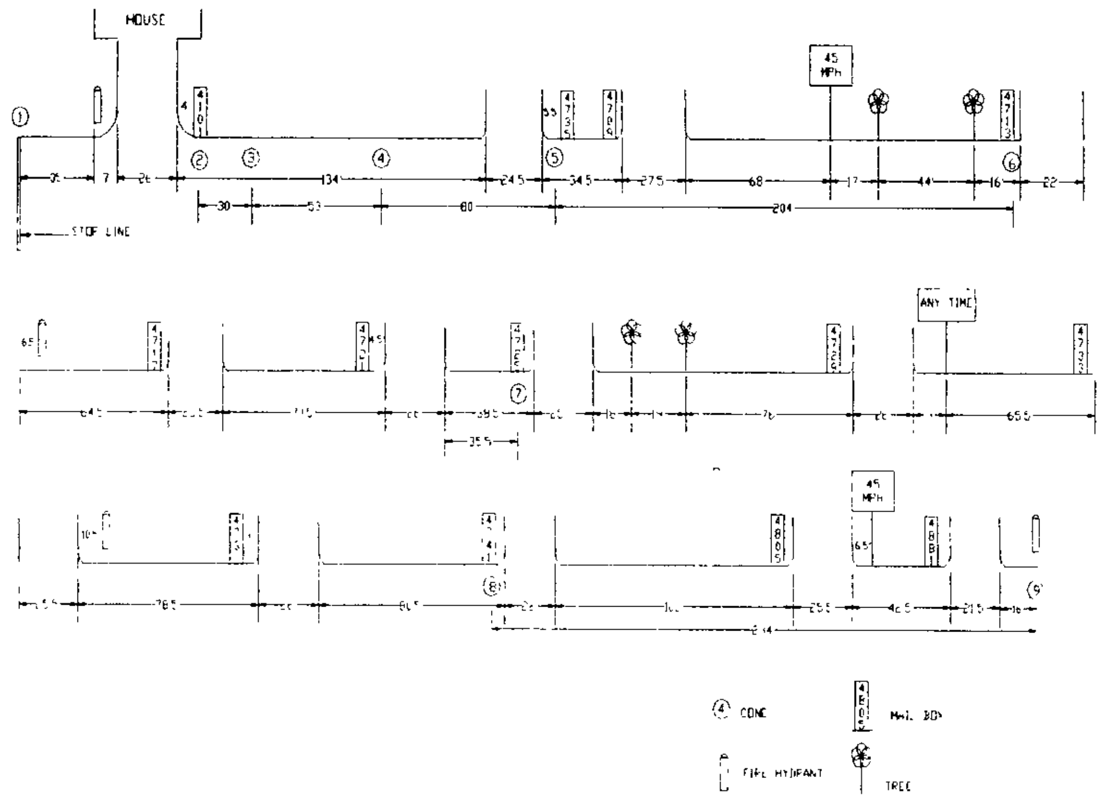
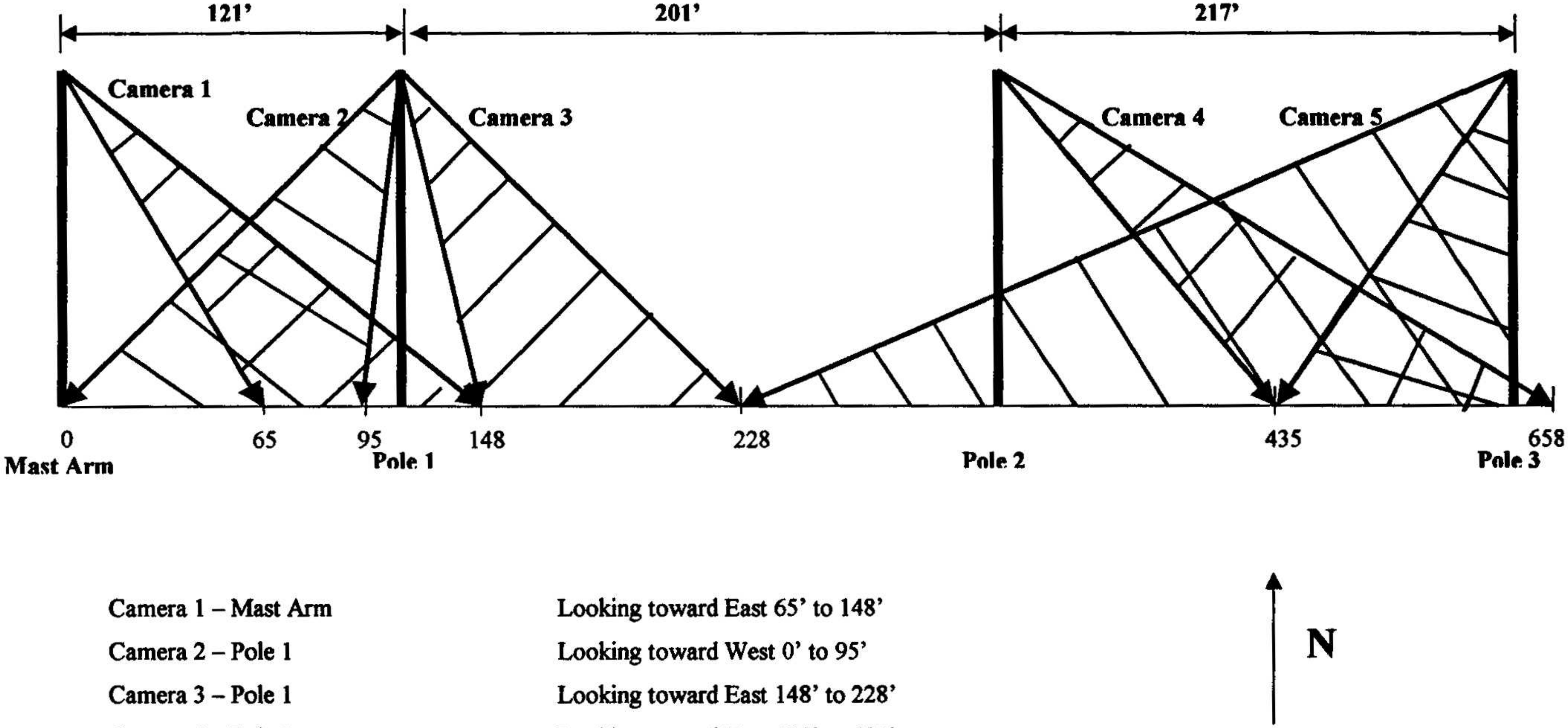


Figure 4 Configuration of Camera Setup at Manchester and Marshal in Middletown



Camera 1 – Mast Arm	Looking toward East 65' to 148'
Camera 2 – Pole 1	Looking toward West 0' to 95'
Camera 3 – Pole 1	Looking toward East 148' to 228'
Camera 4 – Pole 2	Looking toward East 435' to 658'
Camera 5 – Pole 3	Looking toward West 228' to 435'
Camera 6 – Cambridge Dr.	1110' to 1345'

4.1 Data Reduction from Video Tapes

The traffic data were manually reduced from the videotapes, which was time consuming and fairly complicated. Each vehicle was tracked over the approach length of 65'-658' and 1110'-1345' from the stopline with the help of six cameras. Two orange cones were placed on the curb to indicate the limits of each camera's views. The concurrent signal indications (green, yellow, or red) were also recorded in the videotapes. Each vehicle was identified by its color and type on each camera. The clock times on the vehicles' arrival at different positions on the roadway were recorded. Although every attempt was made to manually synchronize the clocks in each camera to the nearest second, a few differences always remained, which required synchronization of the data during the analysis stage.

The research team reduced the vehicular movements and signal indications using a monitor and a Hi-8mm videocassette recorder (VCR) capable of displaying time code on each frame of the videotape at the rate of 30 frames per second. A data reduction method was adopted for maintaining uniformity and consistency among all workers who reduced the data from videotapes. An example of this method is attached in the Appendix. The data extraction included the tracking each vehicle upstream of the intersection when the traffic light turned yellow from green. The time in frames, when a vehicle arrives at the two ends (cones) of each camera view, was recorded. The signal interval change time (i.e. the time in frames at which the change took place) was also recorded for every cycle length. Every vehicle was identified by its color and type, and the lane on which it traveled (right/left). The distance between two successive cone positions was measured. All the extracted information was then entered into Excel spreadsheets for analysis.

4.2 Post-Measurement Synchronization and Dilemma Zone Prediction

A driver is in a dilemma zone when he sees the yellow traffic light but is both too far away from the intersection to cross and too close to the intersection to stop, The consequence is that he will either run the red light or must brake abruptly. This is a potential cause for traffic accidents in the intersections. Given the speed v (in mph) that the vehicle is at the beginning of the yellow light, there is a standard formula for computing the *stopping sight distance* S(v). This is the sum of the reaction distance and the braking distance.

$$S(v) = 3.675v + \frac{v^2}{30f(v)}$$

where $f(v)$ is the coefficient of friction, which is a function of v. The unit for S(v) is foot and that for v is mph.

v (mph)	*f*(*v*)
< 28	0.36
< 30	0.35
< 32	0.35
< 35	0.34
< 40	0.32
< 44	0.31
< 52	0.3
< 55	0.29
≥ 55	0.28

If S(v) is longer than the distance from the vehicle to the intersection when the traffic signal turns yellow, the driver does not have enough distance to stop the vehicle. If it is also the case that the vehicle cannot reach the intersection in the current speed (this happens when the *clearing distance*, or the distance the vehicle travels before the signal turns red, is shorter than the distance to the intersection), the driver is in a *dilemma zone* and in danger of causing an accident. The speed and distance to the intersection at the time when the traffic signal turns yellow are assumed to be the only factors that determine whether the driver will be in a dilemma zone.

4.2.1 Post-Measurement Synchronization

On a segment of highway, how can we observe the speed and location of each vehicle at the moment when the traffic light turns yellow? In this real situation, we were limited with instruments (that is, video cameras) that record local times when the vehicle passes two nearby physical marks (that is, cones) on the roadway segment. These instruments could not be synchronized, although the clock rhythms were accurate, and only one of them is accurately associated with the traffic signal changing times.

To find out the location and thus also the speed of the vehicle when the traffic light turns yellow, it is necessary to synchronize the times recorded by different instruments. Because it was not possible to synchronize the instruments at the site, the synchronization was done after data collection. We call this *step post-measurement synchronization*. This post-measurement synchronization is a parameter-selecting and data-fitting optimization process. The parameters in the models are the clock difference adjustments between the clocks in different instruments. The models are simple prediction functions based on simple assumptions. The optimization goal is to minimize the mean squared error between the prediction and the measurement value, over the available data. The data collected include distances between the intersection and the physical marks, the time at which each vehicle passes each mark, as recorded by the instrument monitoring the mark. Let T denote the set of time sequences recorded by the instruments. Each sequence $t = \{t_1, t_2 ... \ t_n\}$ represents the time values obtained by all the instruments on a single vehicle. The symbol t is also used to represent the particular vehicle. Each instrument monitors two nearby physical marks, and thus the time interval that a vehicle uses to travel from one mark to the other is free of synchronization errors.

Instruments with Overlapping Ranges

When one physical mark is covered by two instruments, the synchronization of the two instruments is done by finding the adjustment value δ such that

$$E = \sum_{i=j=1}^{N} (t_i + \delta - t_j)^2 \qquad (2)$$

is minimized, where t_i and t_j are two values recorded by two instruments as the time at which the vehicle t passed the same physical mark.

The adjustment δ that minimizes E should make $\partial E / \partial \delta = 0$. The only solution to this equation is

$$\delta = \frac{1}{N} \sum_{j=i=1}^{N} (t_j - t_i) \qquad (3)$$

Instruments with Non-Overlapping Ranges

When the intervals monitored by two instruments do not overlap, we have a more complicated situation. Let the times recorded by the two instruments at these marks be $t_1 < t_2$ and $t_3 < t_4$, where t_1 and t_4 are the times a vehicle passes the outer marks and t_2 and t_3 those for the inner marks. Let the distances between marks *i and i*+1 be d_i, The speeds of the vehicle $t \in$ T recorded by the two instruments are

$$v_1 = \frac{d_1}{t_2 - t_1}, \qquad \textit{and} \qquad v_3 = \frac{d_3}{t_4 - t_3}$$

If we assume that the vehicle speed between the inner marks is the average of these speeds, then the vehicle should reach the mark with time t_3 at time

$$t_3' = t_2 + \frac{2d_2}{v_1 + v_2} \qquad (5)$$

We want to find the best time adjustment δ that minimizes

$$E = \sum_{t \in T} (t_2 + \frac{2d_2}{v_1 + v_2} + \delta - t_3)^2, \qquad (6)$$

By letting ∂E / ∂δ=0, we have the solution

$$\delta = \sum_{t \in T} (t_3 - t_2 - \frac{2d_2}{v_1 + v_2}).\frac{1}{N} \qquad (7)$$

Synchronized Time Sequences

Using the post-measurement synchronization method described above, all the times in the sequence t can be calibrated to the time standard set by the instrument monitoring the intersection and the traffic fight. When a physical mark is monitored by two overlapping instruments, the synchronized time is the average of the two calibrated times for that mark. Let us denote this new time sequence by $u = u_1 < u_2 < .... < u_n$ where u_1 is the synchronized time at the mark farthest from the intersection and u_n is the time when the vehicle reaches the intersection.

4.2.2 Synchronization Without the "Green" Vehicles

The synchronization result should obviously be better if the vehicles used in the process are all "green", meaning that the traffic light was all green during the interval when they were on the segment. Experiment showed that the calibration difference is negligible whether the vehicles used in synchronization were all green or all non-green. (The actual maximum difference in δ calculation was 1/30 of a second for our data). Because of this, except the first data set, only non-green vehicles were entered into the data. (This saved considerable time during data reduction.)

4.2.3 Dilemma Zone Calculation

Given the synchronized time sequence *u* for each vehicle, it is possible to compute whether the vehicle was in a dilemma zone.

4.2.4 Yellow Time Calculation

Suppose the instrument monitoring the intersection records all the times at which the traffic light turns yellow. Because the traffic light goes through a fixed cycle, by averaging all the differences between successive yellow beginning times, a simple formula can be found for all the yellow beginning times. The formula is that $y(u)$, the time when a vehicle u may see the beginning of yellow before reaching the intersection is the value

$$y(u) = \max_{k=0,1,..} \{a + kb; a + kb < u_n\} \tag{8}$$

where, a and b are estimated using all the yellow beginning times recorded.

4.3 Speed and Location at Yellow

Speed at Yellow

If $y(u) > u_0$, then the vehicle u was on the segment while the traffic light turned yellow. Based on the slot $I(u)$ where $y(u)$ falls in ($u_{I(u)} \leq y(u) < u_{I(u)+1}$), the speed of the vehicle $v(u)$ when the light turns yellow can be found. (($d_{I(u)}$ / ($u_{I(u)+1}$ - $u_{I(u)}$) seems to be less robust than the average of the speeds in the neighboring slots when the slot was not monitored by any instrument).

Location at Yellow

Let L_i be the distance between the physical mark corresponding to u_i and the intersection (L_n = 0). The exact location of the vehicle at the yellow beginning time can be found using the formula

$$L(u) = L_{I(u)} - v(u)(y(u) - u_{I(u)}). \tag{9}$$

4.4 In a Dilemma Zone?

Whether a vehicle is in a dilemma zone $u \in D$ is determined by the following conditions.

$$D = \{u \in U; v(u)T < L(u) < S(v(u))\} \quad (10)$$

where T is the time interval length during which the traffic light stays yellow.

4.5 Dilemma Zone Prediction and Avoidance

Using the method discussed above, a subset D is singled out from the set of data T, where each vehicle in D is believed to have been in a dilemma zone. How can this data be used to make prediction in the field? First, we have to decide what information would be available in the field and how early do we have to know the information before a decision can be made to alter the yellow beginning time and help the vehicle to avoid the dilemma zone. Using a similar instrument at somewhere (L_0, for example) upstream of the intersection, we can measure the speed and time a vehicle passes the point. The time is only useful when it is compared to the next yellow beginning time. Therefore, the information the instrument collects consists of the initial speed and the lapse of time before the traffic light turns yellow.

4.6 Table of Dilemma Zone Data

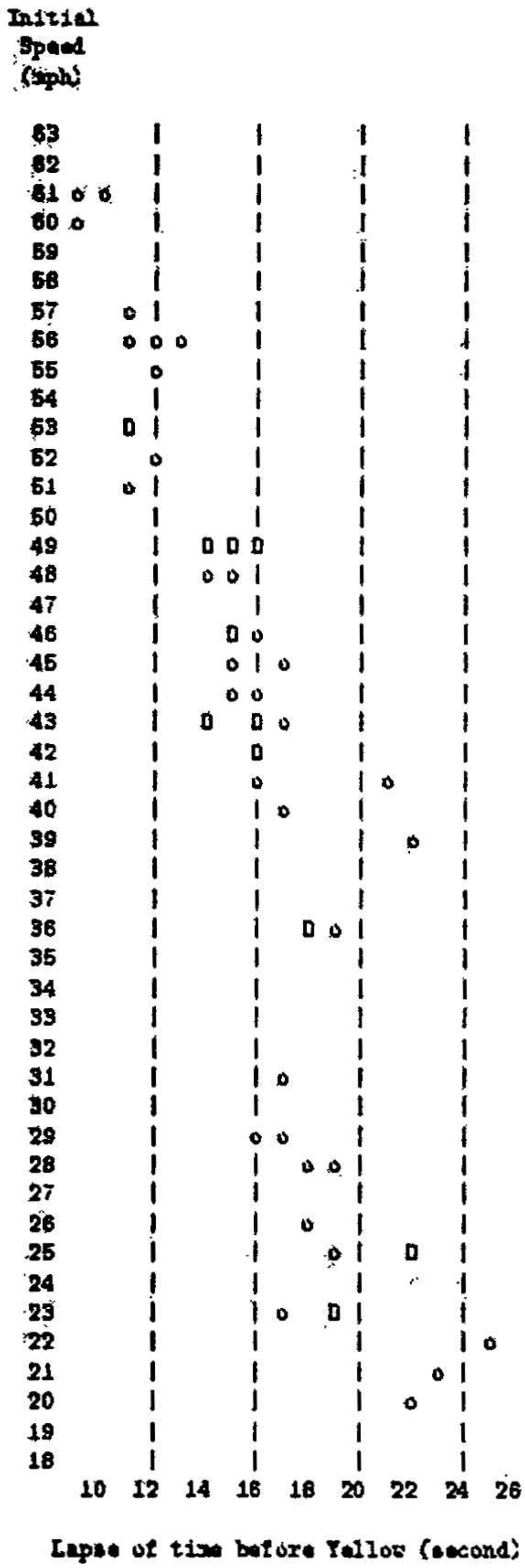
Using these two pieces of information as coordinates, we can plot the range of D in a two-dimensional table. A total of 352 vehicles with complete data and reasonable speed, which crossed the intersection during yellow light, were identified. The analysis showed that 62 vehicles experienced dilemma zone. Attached is a table based on these 62 vehicles where a small O indicates a single event and a big ☐ multiple events. (An event is defined as a vehicle caught in a dilemma zone). This table can be used as an example of data to predict whether a vehicle entering this particular segment with a certain initial speed and a certain lapse of time before yellow is likely to be in a dilemma zone.

4.7 Conclusions from This Study

The data collected and displayed in Table 5 show that for almost all instances, dilemma zones for approaching vehicles can be eliminated with an adaptive green extension or cutback before yellow and the maximum extension or cutback need to be no more than 2 seconds.

However, the green extension or cutback before yellow for the sake of one approaching vehicle may affect the chances that the preceding or the following vehicles will be caught in the dilemma zone. To find out the optimum strategy for green extension when multiple approaching vehicles are involved, we developed a technique whereby (a) all vehicles that would be caught in a dilemma zone are predicted by tracking vehicles on the entire roadway during a few seconds before the green light changes to yellow; (b) an optimum strategy to reduce/eliminate dilemma zone for these vehicles on the entire roadway segment is determined; and (c) the strategy is implemented by the signal controller. This new technique is described in the next chapter.

Table 5 Plot of Vehicles Caught or Likely To Be Caught In Dilemma Zone



5 NEW TECHNIQUE FOR DILEMMA ZONE REDUCTION BY ADAPTIVE SIGNALING

The yellow interval in traffic signal timing is designed to allow drivers to decide either to stop or to drive through the intersection before the following red interval begins. When the speed and the location of the vehicle is such that the driver cannot stop and also cannot drive through in time, the vehicle is said to be in a *dilemma zone*. For a fixed speed v, there is a minimum distance before the vehicle can stop (the *stopping sight distance*), and there is a maximum distance that the vehicle can travel through during the yellow interval (the *clearing distance*). If the vehicle's current distance to the intersection is smaller than the stopping sight distance but larger than the clearing distance, then it is in the dilemma zone.

Assume that a series of detectors are placed on the roadway upstream of an intersection in such a way that they can simultaneously record the position and speed of all vehicles on the roadway. With the information provided by these detectors, it is possible to predict whether these vehicles will be caught in dilemma zones. With such prediction before the end of a green interval, it is possible for the traffic controller to extend or cutoff the green interval, so that the beginning of yellow is postponed or accelerated to allow these vehicles to either stop or clear the intersection by maintaining the current speed..

The Middletown study described in the previous chapter suggested that the maximum extension or cutback needed to get a vehicle out of a dilemma zone is generally no more than 2 seconds for a common traffic setting. But although the extension or cutback may allow some vehicles to stay away from a dilemma zone, it may also cause the following vehicles to get caught in dilemma zone. Therefore, the extension or cutback must be done not only based on those vehicles that will be in a dilemma zone without it, but on those that will be in a dilemma zone because of it as well.

Theoretically, one can keep extending or cutting back the green interval until no vehicle falls in a dilemma zone, and thus reduce the number of vehicles in a dilemma zone to zero. However, this may increase the delay time for the cross traffic and reduce the overall speed of the traffic. Therefore, an upper bound for the green interval extension or cutback should be set.

Also, in order to maintain the orderly rhythm in the coordination of a series of traffic signals, one may want to maintain the overall length of the signal cycle, which is often computed using some optimization program. This requires the compensation of each extension to a green interval by the contraction of a following green interval (either one for the current direction or the one for the cross traffic) and vice versa.

In this and subsequent chapters, we describe an adaptive signaling strategy that involves the calculation of an optimal extension and cutback of green interval. We implement this strategy by modifying the NETSIM source codes and report the results from computer simulation of the proposed strategy on real traffic data over a multi-intersection corridor.

From the computer simulation, we will show that the proposed adaptive signaling strategy will significantly reduce the number of vehicles in a dilemma zone, without increasing average delay time. The conjecture is that this simple adaptive signaling strategy will significantly reduce dilemma zone cases and thus the possibility of traffic accidents, without sacrificing the optimal delay time based on a fixed pre-timed signal control.

5.1 Dilemma Zone on the Time Line

The dilemma zone for vehicles of a given speed is often visualized as an interval in terms of distance from an intersection. Given the current location and speed of a vehicle approaching an intersection, it can also be viewed as an interval in the time line. The time scale may mean the number of seconds before the beginning of the next yellow interval.

The distance-based dilemma zone formula is that a vehicle with speed v and at a distance d from the intersection will be in a dilemma zone if

$$vy < d - tv < av + \frac{v^2}{bf(v)} \qquad (1)$$

where y is the length of the yellow interval in seconds, $f(v)$ is the coefficient of friction at speed v, and a and b are constants in the formula for stopping sight distance computations.

This distance-based dilemma zone formula can be converted into a time-based formula as follows:

$$\frac{d}{v} - \frac{v}{bf(v)} - a < t < \frac{d}{v} - y \qquad (2)$$

If the currently scheduled beginning of the next yellow interval is t_0 seconds away, then the vehicle will be in a dilemma zone if it maintains the current speed and t_0 falls in the above interval.

5.2 Finding the Optimal Extension Time

Assume that a traffic controller can record both the speed and distance of all vehicles on the link approaching an intersection in a green interval that is t_0 seconds before its end. Using this information, the time-based dilemma zones of these vehicles can be computed. One can also compute a function of time, $g(t)$ that is the number of vehicles that will be caught in a dilemma zone when yellow interval begins t seconds from now.

Given an upper bound T to the extension/cutback time and the remaining time t_0 to the scheduled end of the current green interval, the optimal extension/cutback time for this green interval is the smallest t between t_0 and t_0 + T that gives the smallest $g(t)$ over the interval. If [t_0, t_0 + T] is zero, there exists an extension or cutback that will free all approaching vehicles from the dilemma zone. When the smallest t for the smallest $g(t)$ is t_0, the best policy is not extending or cutting back at all.

One can adopt a policy that if we scan the vehicles on a link just a few seconds before the beginning of a yellow interval, we may be able to extend the green interval so that the vehicles can avoid the dilemma zone. During each clock cycle, we can identify those links that are in the last few seconds of the pre-yellow green interval. We can compute whether the vehicle is in a dilemma zone and increment the dilemma counter. The vehicle will have stopping sight distance according to the current speed v. Thus we can determine if the vehicle will be in a dilemma zone if the green time is extended (or cutback) by t seconds. Thus, for each vehicle approaching an intersection on the link that is about to turn yellow, there is a time interval such that (a) the vehicle will be in dilemma zone without green extension (or cutback) or (b) it will be in dilemma zone when there is T seconds of extension (or cutback). So the task is to find the smallest nonnegative integer T that is not in any of these time intervals and extend (or cutback) the current interval by T seconds. This T can always be found and thus, without other restrictions, all dilemma zones can be avoided.

Of course, once the current interval is extended (or cutback), the last second of it will be encountered in a later iteration. If we make the correct choice of T, then no vehicle should be in dilemma zone in the extended (or cutback) interval and the extension (or cutback) is done at most once for each green interval.

In reality, there may be some constraints to extending (or cutting back) the green intervals. In the simulated study described in the next chapter, we assumed that this should be no more than 6 seconds and also the cycle length should be maintained. To compensate the extension (or cutback), we can reduce (or increase) the next green interval on the cross street or the main street. This can be implemented using a global variable memorizing the extension (or reduction) and at the beginning of each green interval, the reduction (or increase) is done.

5.3 Summary of New Technique

In summary, the new technique consists of the following steps:

(a) Step 1 - Detection of the positions and speeds of <u>all</u> vehicles on the roadway before the green light changes to yellow. The detection of these vehicles may begin a few seconds before the scheduled end of the green interval. This will require a series of detectors or pseudo-detectors that will provide the position and speed of each vehicle on the roadway at small time intervals (1 sec).

(b) Step 2 - Prediction of the number of vehicles that would be caught in a dilemma zone, if no action is taken. This prediction can be done by calculating stopping sight distance and clearing distance using time-based formula for dilemma zone.

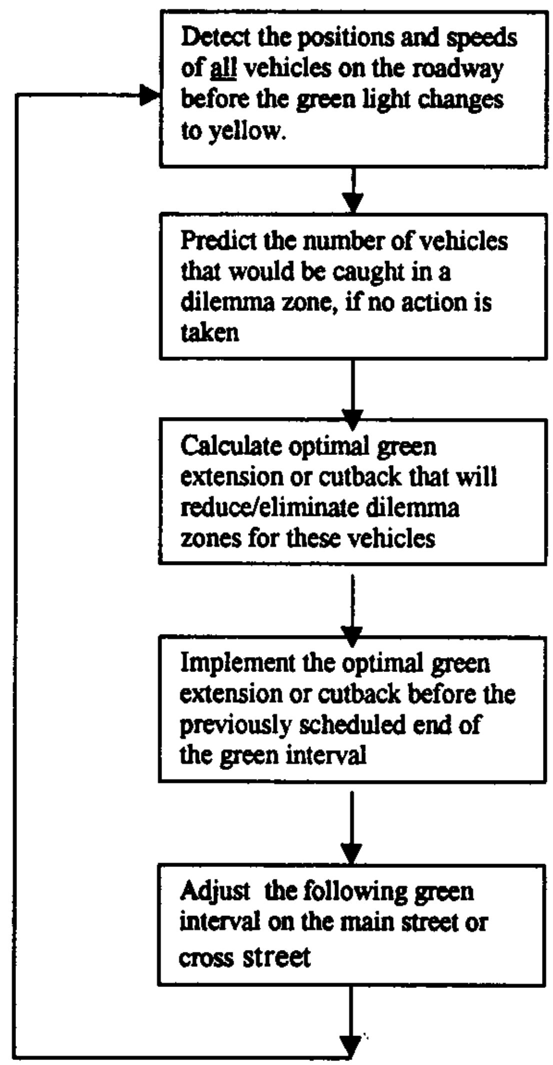
(c) Step 3 - Calculation of the optimal green extension or cutback that will reduce/eliminate dilemma zone problem for these predicted vehicles. The extension or cutback is not only based on those vehicles that will be in a dilemma zone without it, but on those that will be in a dilemma zone because of it as well.

(d) Step 4 – Implementation of the optimal extension or cutback by the traffic controller before the previously scheduled end of the green interval.

(e) Step 5 – Adjustment of the following green interval on the main street or cross street to compensate for the green time that was extended or cutback. This will maintain the previously designed cycle length in the corridor.

(f) Step 6 - Repeat the whole process of detection, prediction, extension/cutback, and implementation during each green interval.

Figure 5 Flow Chart of New Technique



6. SIMULATION RESULTS

The stopping sight distance is computed as

$$S(v) = 3.675v + \frac{v^2}{30f(v)}$$

where $f(v)$ is the coefficient of friction, which is a function of v. The unit for S(v) is foot and that for v is mph.

At the end of a green interval, when the distance of a vehicle to the intersection is shorter than the stopping sight distance, it cannot stop before reaching the intersection, and thus the only choice is to drive through or stop abruptly. But, if the current speed is maintained, it can only travel vt where t is the length of the yellow interval, and when this is shorter than the distance to the intersection, the vehicle is in a dilemma zone.

In this chapter, we will show that the number of vehicles in a dilemma zone can be computed using NETSIM that was modified by the researchers. The program keeps track of the time and position of each vehicle in the network. When the signal turns yellow after the end of the green interval, it can find all vehicles on the link and compute their distances to the intersection. The speeds of the vehicles are also known. Whether the vehicle is in a dilemma zone can be computed using this information. When the signal is green, one can still predict whether a vehicle on a link will be in a dilemma zone. But we have to assume that the vehicle will not turn and it will maintain the current speed until the yellow light.

6.1 Modification of NETSIM Source Code

The NETSIM program, developed by the Federal Highway Administration and currently distributed through the University of Florida McTrans Center, simulates various traffic operations of an arterial corridor. NETSIM models traffic stochastically, using the Monte Carlo technique. The program keeps track of the time and position of each vehicle in the network. When a vehicle approaches a traffic signal, one of the following actions will occur. If the signal is red, deceleration of 1ft/sec^2 is applied until the vehicle speed has dropped 10 percent then a deceleration rate of 7 ft/sec^2 is applied until the vehicle halts. If the signal turns yellow, and if the vehicle's position is at a distance closer than the safe stopping distance from the stop line, the vehicle will proceed without stopping. If the position of the vehicle is at a distance greater than the safe stopping distance, the vehicle will stop behind the stop line. If the signal is green, the vehicle will proceed without stopping.

Since NETSIM does not simulate dilemma zone conditions for vehicles in a network, it was necessary to modify the source codes of NETSIM so it will incorporate the technique for reducing dilemma zone developed in this study. The source codes for NETSIM were obtained from McTrans Center on a special arrangement with the University of Cincinnati. The following four source files were modified:

(a) C:\TRAF\NETSIM\NETSIMN.FOR

The subroutine NETSIM(ISTEP,WCASE) was separated and a new file NETSIMN0.FOR was formed. The modifications were inserted between the characters C***.

(b) C:\TRAF\CORSIM.EXE\MAKEFILE.NET

The name of the source file NETSIMN0.FOR was added in line 111 so it could be recognized by the Fortran compiler.

(c) C:\TRAF\GLOBAL\GLOBAL.INC

A global variable POLICY was declared to decide whether the dilemma zone reduction would be implemented or not.

(d) C:\TRAF\GLOBAL\GLOBALNZ.FOR

The modified codes were inserted between the characters C***. The purpose was to read the input variable POLICY and the maximum green time extension.

The technique developed for the reduction of dilemma zone and incorporated in the Modified NETSIM was applied first on a hypothetical corridor consisting of 11 signalized intersections and then on the US 33 corridor between Henderson Road and Riverside Green Road in Columbus, Ohio. The simulation was performed in three steps involving the use of PASSER-II, TRANSYT-7F and the Modified NETSIM v5.0 program. It may be noted that the delay values calculated by these programs are not directly comparable since each program uses a different method for calculating delay.

PASSER II was developed by the Texas Transportation Institute of the Texas A&M University system. PASSER II selects the best available phase sequence at each intersection to maximize overall arterial progression. After selecting the optimum phase sequences, phase lengths and progression offsets are calculated. Measures of effectiveness (MOE's) are calculated for each traffic movement to evaluate the level of service and time space diagrams are provided to show the progression scheme visually.

The turning movements and signal phasing information was input into PASSER II and analyzed for maximum signal progression. Initially it was run for different cycle lengths (50 –120 sec). After choosing the optimal cycle length, the software was run to give the maximum bandwidth and phase settings. The PASSER II output report included the following: (I) offsets (ii) phase timing or splits for each phase combination (iii) time-space diagram along with green band in both directions of arterial. The bandwidth calculated by PASSER II is the maximum that can be obtained in the given traffic conditions.

The drawback with using this timing plan is that, even though it provides the maximum bandwidth, it does not necessarily mean the least delay. For the purpose of minimizing delay the software TRANSYT-7F was used. TRANSYT-7F was originally developed under contract to the Federal Highway Administration by the University of Florida Transportation Research Center. TRANSYT-7F can estimate traffic performance measures such as delay and stops. When optimizing, TRANSYT-7F minimizes an objective function called the Performance Index (PI). The PI , which is a disutility, is either a linear combination of delay and stops, fuel consumption and excessive maximum back of queue or excess operating costs.

Although TRANSYT-7F minimizes delay, it does not give the maximum bandwidth. But the software allows the user to specify the bandwidth constraint. Using this provision, the maximum bandwidth obtained from PASSER II was set as a constraint and the software was made to minimize delay. The input to TRANSYT-7F included the phase sequences, phase splits, green bands for both directions obtained from PASSER II, the geometry information of the arterial, and the free flow speed. TRANSYT-7F after the optimization run provided the optimized signal timing and offsets, which provided the maximum bandwidth and the minimum delay. TRANSYT-7F was also run in simulation mode with the phase settings obtained from PASSER II. Since both PASSER II and TRANSYT-7F programs deals with groups or platoons of vehicles, it was not possible to determine specific vehicles experiencing dilemma zone problems. Hence, we used the optimized timing plan obtained from the previous analysis in a program which consisted of a microscopic simulation model. For this purpose the network simulation software NETSIM was used.

Because NETSIM is a simulation program that has a clock increment of one second, fractional extensions were ruled out. The time function $g(t)$ was implemented as an array with each element for an integral extension for an intersection.

The green time reduction to each extension was implemented at the beginning of the next green interval (for the cross traffic), so the overall length of the signal cycle was a constant suggested by the optimization program. The results of these simulations are provided in the following sections.

6.2 Simulation of 11-Intersections Corridor

A hypothetical data set was used to test the new technique using the Modified NETSIM v5.0 program aimed at reducing the dilemma zone problem. The data set included 11 intersections along the test corridor, from First Street to Eleventh Street with a total length of 13300 ft.

(a) In the first set of runs, PASSER-II program was used to optimize signal timing based on maximization of green bandwidth for progression. The geometry and traffic data was input to PASSER-II, which was run with cycle length ranging from 50 to 120 second based on a cycle increment of 10 seconds. A final run was made with 55 sec of cycle length, which provided the maximum bandwidth. This optimized timing was utilized to build the NETSIM network. After running the Modified NETSIM program, the number of vehicles that experienced dilemma zone under different green time extensions for through traffic on the corridor was recorded. The result showed that the number of vehicles experiencing dilemma zone reduced from 873 with no extension to 61 with 5 seconds of extension (Table 5)

Table 6 Simulation Using PASSER-II and Modified NETSIM

Max Allowed Extension(sec)	0	1	2	3	4	5
# of veh in dilemma zone	873	526	336	103	103	61
Ave. delay (min/ml)	0.64	0.62	0.62	0.61	0.61	0.60
Ave. delay (sec/veh)	0.64	0.62	0.62	0.58	0.6	0.56

(b) In the second run, the same traffic and geometric data was input to the TRANSYT-7F program to optimize signal timing based on delay minimization. This set of timing data was also run by the Modified NETSIM program under different green time extensions, which gave us the number of vehicles experiencing dilemma zone. As can be seen from Table 6, the number of vehicles experiencing dilemma zone reduced from 1155 with no extension to 68 with 5 seconds of extension. Also note that the number of vehicles experiencing dilemma zone with no extension were higher for this run than for the previous run.

Table 7 Simulation Using TRANSYT-7F and Modified NETSIM

Max Allowed Extension(sec)	0	1	2	3	4	5
# of veh in dilemma zone	1155	742	535	251	84	68
Ave. delay (min/ml)	0.69	0.67	0.66	0.63	0.63	0.66
Ave. delay (sec/veh)	0.70	0.68	0.67	0.62	0.59	0.59

(c) In the third run, we first used the PASSER program to run the initial traffic and geometric data, then used the resulted bandwidth and offset as a constraint in TRANSYT-7F program. The optimized signal timing from TRANSYT-7F was run by Modified NETSIM program under different green time extensions. The number of vehicles experiencing dilemma zone in the corridor were recorded. The result showed that the number of vehicles experiencing dilemma zone reduced from 859 with no extension to 48 with 5 seconds of extension, which was the lowest number among the three runs (Table 7).

Table 8 Simulation Using (PASSER-II + TRANSYT-7F) and Modified NETSIM

Max Allowed Extension(sec)	0	1	2	3	4	5
# of veh in dilemma zone	859	573	368	112	66	48
Ave. delay (min/ml)	0.65	0.63	0.62	0.61	0.60	0.61
Ave. delay (sec/veh)	0.65	0.64	0.63	0.58	0.56	0.55

As we can see from the results of the simulation runs, after we implement the adaptive signal timing strategy, the number of vehicles experiencing dilemma zone dropped drastically in each of the three runs. Without the implementation of the dilemma zone reduction strategy, the results showed that there were less dilemma zone problems in the PASSER and PASSER+TRANSYT runs, which showed that signal timings based on bandwidth maximization or a combination of bandwidth maximization and delay minimization have lower number of vehicles experiencing dilemma zone than signal timing based on delay minimization alone. The third run had the best result with the minimum number of dilemma zone problems. It combined the advantages of PASSER and TRANSYT programs with both maximization of bandwidth and minimization of delay.

In this study, a unique extension time for the overall network was specified, which was implemented in each intersection. However, for optimal performance, different intersections may benefit by using different extension times. In the future, different extension times for different intersections may be considered so that the best combination of extension times can be used. Also, in future implementations, if necessary one can use a fraction of second as an extension time to improve the preciseness of implementation, if this can be implemented by the signal controller.

6.3 Simulation of US 33 Corridor in Columbus, Ohio

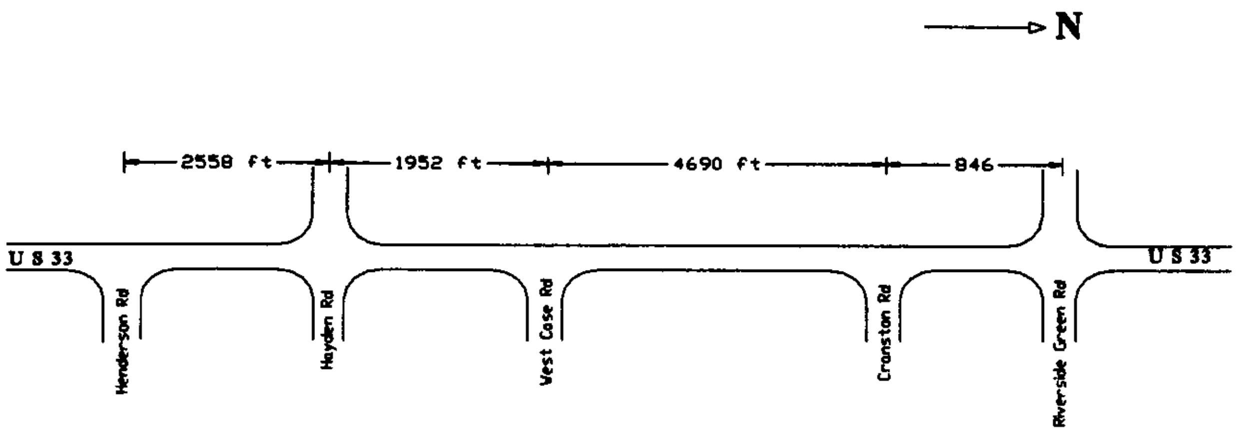
The technique developed for the reduction of dilemma zone was implemented on the US 33 corridor between Henderson Road and Riverside Green Road. This site had a free flow speed of 50 mph (>35 mph) during the hours of 10:00am-11:00am and the arterial had closely spaced intersections (1000-2000 feet). The schematic representation of the study area is shown in the Figure 6. The five intersections are listed as follows:

1. Henderson Road.
2. Hayden Road.
3. West Case Road
4. Cranston Road
5. Riverside Green Road.

More figures for each intersection along with the turning movements of each intersection are attached in the Appendix.

The traffic volume count for each intersection and spot speeds for different segments of the corridor was provided by ODOT. The geometry of the corridor and signal phasing of the intersections was obtained from the drawings also provided by ODOT.

Figure 6 Line Sketch of US 33 between Henderson and Riverside Green Road



Not to Scale

The results of the final simulation run are shown in Table 8.

Table 8 Simulation Using (PASSER-II + TRANSYT-7F) and Modified NETSIM

Max Allowed Extension (sec)	0	1	2	3	4	5	6	7
Vehicles in Dilemma Zone	173	120	87	63	50	49	38	40
Average Delay (min /ml)	0.93	0.91	0.89	0.90	0.89	0.90	0.89	0.89
Average Delay (sec / veh)	1.07	1.05	1.03	1.04	1.02	1.03	1.02	1.02

From this result, we can see that an implementation of the adaptive signaling strategy reduced the dilemma zone encounter from 173 to 38 for an extension time of 6 seconds.

We found that the optimum maximum extension should be related to the individual intersections. Indeed, if our simulation allowed different settings of this maximum extension for different intersections, the total number of dilemma zone encounters may be reduced to 28 (current best: 38 for the maximum extension time 6 seconds).

7 CONCLUSIONS AND RECOMMENDATIONS

A feasibility study of dilemma zone problems was performed by collecting and analyzing traffic flow data at a high-speed signalized intersection approach in Middletown, Ohio. Vehicles were tracked with six cameras on a 1345-ft long segment of an intersection approach. A method was developed to synchronize the vehicles' movements between the sub-segments covered by each camera. The speed and location of the vehicles when the signal turned yellow were determined. Based on this information and the computed stopping and clearing distances, it was possible to determine if a vehicle was in a dilemma zone. Further analysis of the data for all vehicles that were in a dilemma zone revealed that the maximum green extension or cutback needed to get a vehicle out of the dilemma zone is generally no more than 2 seconds.

Although an extension or cutback of green interval may allow some vehicles to stay away from a dilemma zone, it may also cause the following vehicles to fall into dilemma zone, Therefore, the extension or cutback must be done not only based on those vehicles that will be in a dilemma zone without it, but on those that will be in a dilemma zone because of it as well. Theoretically, one can keep extending or contracting the green interval until no vehicle falls in a dilemma zone, and thus reduce the number of vehicles in a dilemma zone to zero. However, this may increase the delay time for the cross traffic and reduce the overall speed in the arterial corridor. Therefore, an upper limit for the green interval extension or cutback should be set. Also, in order to maintain the orderly rhythm in the coordination of a series of traffic signals, one may want to maintain the overall length of the cycle length, which is often computed using some optimization program. This requires the compensation of each extension or cutback to a green interval by the cutback or extension respectively of the following green interval (either one for the current direction or the one for the cross traffic).

One can adopt a policy that if we scan the vehicles on a link just a few seconds before the beginning of a yellow interval, we may be able to extend or cutback the green interval so that the vehicles can avoid the dilemma zone. For each vehicle approaching an intersection on the link that is about to turn yellow, there is a time interval such that (a) the vehicle will be in dilemma zone without green extension (or cutback) or (b) it will be in dilemma zone when there is T seconds of extension (or cutback). So the task is to find the smallest nonnegative integer T that is not in any of these time intervals and extend (or cutback) the current interval by T seconds. This T can always be found and thus, without other restrictions, dilemma zones can be avoided. If we make the correct choice of T, then no vehicle should be in dilemma zone in the extended (or cutback) interval and the extension (or cutback) is done at most once for each green interval. In reality, however, there may be some constraints to extending (or cutting back) the green intervals. One may assume that this should be no more than 5 or 6 seconds and also the cycle length should be maintained. To compensate the extension (or cutback), we can reduce (or increase) the next green. interval on the cross street or the main street.

Our simulation study, performed by modifying the source codes of NETSIM, showed that the signal timing generated by a bandwidth maximization program (PASSER-II) resulted in lower number of vehicles in dilemma zone than that generated by a delay minimization program (TRANSYT-7F). Additionally, the signal timing generated by the combination of the two programs, that is, by minimizing delay within the constraint of bandwidth maximization, resulted in even lower number of vehicles in dilemma zone than those generated by each program alone.

The technique developed in this study can be implemented if the speeds and positions of all vehicles on the roadway can be recorded at small time intervals (e.g. 1 sec). A series of detectors can be installed on the roadway. Ideally, one would like to space these detectors at spacings of 25 ft. so the positions and speeds for all vehicles can be recorded for a few seconds before the scheduled end of the green interval. By knowing the position and speed of each vehicle as provided by a detector, the stopping and clearing distances for the vehicle can be computed and a determination can be made if this vehicle will be caught in dilemma zone. Given an upper limit of the extension or cutback time and the remaining time to the scheduled end of the current green interval, the optimal extension or cutback time for this green interval, which is the smallest time (sec) that gives the smallest number of vehicles in dilemma zone, can be calculated. This will determine if there exists an extension or cutback that (a) will free all approaching vehicles from the dilemma zone, (b) will eliminate dilemma zone for some, but not all, vehicles, or (c) the best policy is not extending or contracting at all.

We recommend that the dilemma zone technique be implemented and tested in the following way:

(1) Select an arterial with 3-5 signalized intersections that has an operating speed of 35-60 mph during a few, if not all, hours of the day. Make sure that the existing equipment (e.g. controllers) can be interfaced with the special software to be developed by the researchers (described in (5) below). With the cooperation of the equipment manufacturer, this task can be completed without infringing upon the proprietary nature of the manufacturer's software.

(2) Use the technique of combining bandwidth maximization and delay minimization to develop optimal signal timings for the arterial corridor. Implement and fine tune these signal timings on the arterial corridor.

(3) Collect "before" data on (a) the percentage of vehicles experiencing dilemma zone, and (b) average vehicular delay. Since the percentage of vehicles experiencing dilemma zone cannot be directly measured in the field, the following surrogate measures can be used by recording the number of vehicles:
    (a) Running red light;
    (b) Stopping abruptly; and
    (c) Accelerating through yellow light.

    Delay can be measured by driving test vehicles in the corridor.

(4) Procure and install video imaging systems including cameras on the upstream roadway segments of each intersection. Using the video imaging software, install a series of pseudo-detectors on the roadway lanes so the position and speed of each vehicle can be recorded accurately. Ideally, a detector spacing of 25 ft is suggested. If this spacing is not possible, higher spacings can be used.

(5) Write software codes to implement the technique for reducing dilemma zone developed in this study. Interface this software with the equipment manufacture's software and implement the technique on the arterial system.

(6) After allowing for a familiarization period, collect "after" data on (a) the percentage of vehicles experiencing dilemma zone, and (b) average vehicular delay, as in (3) above.
(7) Examine the "before" and "after" data.
(8) Submit a final report describing the completed tasks, accomplishments, findings, conclusions, and recommendations.

8 REFERENCES

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APPPENDIX

Data Reduction Suggestions

1. Start with Camera 2. Draw erasable marks on the screen for Cone 2 (a line connecting Cone 2 and the tip of the L in ”ONLY” is perpendicular to the road). This is about 68 feet from the stop line. If the stop line is visible, then any location between Cone 1 and Cone 2 can be identified by measuring the proportion.

2. Start the tape from the beginning, using TC to display the tape time (frame labels) on the monitor screen. Record the beginning tape tune of each yellow period. It seems that they are about 70 seconds apart. The yellow period is exactly 4:00 second long, and the red period is about 10 seconds. Watch those vehicles reaching Cone 2 during the yellow and red periods, except those at the and of the red period. Record the tape time when the bottom of the left front wheel crosses the line you drew on the screen (the bottom of the wheel is the only point invariant from different viewpoints). Record distinguished features of the vehicles, so they can be recognized from other tapes among other vehicles. Record type and color of vehicle and other features and whether they are on the left or right lane. Ignore those in the left turn lane.

3. For each vehicle in the yellow and red period, record their behavior including whether it begins to cross the intersection in yellow or red, whether it stops, brakes (visible from flesh in the rear lights), or turns right in the right lane. If possible, also record the tape time when it reaches some location other than Cone 2 (for instance, when it reaches the 4 feet line, or the 58 feet line).

4. An efficient way to stop the tape at the desired tape time (for instance, the expected beginning of the next yellow period) is to use the ”shuttle” feature by pressing the shuttle button and maintaining the knob in the protruded position. When the knob settles in the neutral position (you can feel it), the frame becomes stationary. When the knob is set in a position toward right, the tape is forwarded in a fixed speed frame by frame. To fast forward the tape, rotate the knob to the rightmost position.

5. There are about 100 yellow periods on a two-hour tape. After the initial learning period, you should be able to process Camera 2 tape in 4-6 hours. Tabulate the data so it is easy to use later.

6. The next tape is that from Camera 1. Cone 2 is again visible and the line between Cone 2 and the tip of L in ”ONLY” can also be drawn. This allows you to measure the tape time difference between the tapes for Camera 1 and Camera 2, as long as there is an unmistakable vehicle in the image. Using this time difference, you can anticipate the arrival of each vehicle with Camera 2 tape time on the table you have constructed. Using fast forward, you should be able to track all vehicles on the table in about 3 hours and record their arrival tape time at Cone 3, or the 95 feet line.

7. Then process Camera 5 and 4, which share Cone 6. Try to find another physical mark in each and record the tape time for the vehicles. Again, once you find the tape time difference of a vehicle between Camera 2 and Camera 5, fast forward can be used to accelerate your search and each tape should be processed in about 3 hours.

8. Finally, Camera 6 should cover Cone 9 and some other physical mark.

9. Record abnormal situations for each vehicle, including braking, changing lanes, entering from Cambridge Drive or another side street.

This is the data reduced from 7-7-97 Tape 1 Cameras 1,2,3.
Camera 2 tape time 00:01:09:02 is time 8:58:36 am.
Camera 1 tape time + 39:13 = Camera 2 tape time.
12.

In the following,

columns 1-2: label;
columns 4-13: preceding yellow beginning Camera 2 tape time;
columns 15-19: Camera 2 tape time when the left front wheel of the vehicle crosses the 67.7 feet line, or Cone 2;
columns 21-25: Camera 2 tape time when the left front wheel of the vehicle crosses the 4 feet line or otherwise indicated in comments following @;
columns 27-31: Camera 1 tape time when the left front wheel of the vehicle crosses Cone 3, or the 95 feet line;
columns 33-42: Camera 3 tape time when the left front wheel of the vehicle crosses the 200 feet line;
columns 44-48: Camera 3 tape time when the left front wheel of the vehicle crosses Cone 4, or the 148 feet line;
columns 50-: Comments, including color when confusing and

L: left lane
R: right lane
C: car
V: van
W: wagon
P: pickup
J: jeep
T: truck
S: make a right turn during yellow or red
X: drive throuth during yellow
Z: drive through during red
@58: column 21-25 is the tape time when the left front wheel crosses the 58 feet line in stead of the 4 feet line, similarly for other numbers.

Y = Arrived at 67 ft during yellow
I = " " " red
G = " " " green

```
          1         2         3         4         5
12345678901234567890123456789012345678901234567890
 1 0:01:09:02 24:00 27:23 43:11 0:01:15:22 16:25 LC grey
 2 0:01:09:02 27:23 34:20 46:17 0:01:18:11 19:19 LC @17 blue
 3 0:03:29:05 49:10 53:28 08:04 0:03:38:13 40:11 RC
 4 0:04:38:26 43:05 45:25 03:01 0:04:36:15 37:04 LC
 5 0:05:48:24 49:28 50:24 10:06 0:05:44:03 44:19 RVX
 6 0:05:48:24 59:28 02:24 19:20 0:05:52:24 53:18 RWS
 7 0:06:58:24 12:27 18:27 32:13 0:07:05:10 06:05 RW
 8 0:06:58:24 16:15 21:13 35:16 0:07:07:26 08:27 RC @28
 9 0:10:28:19 32:00 34:09 51:26 0:10:25:03 25:25 RVS FedEx
10 0:11:38:17 41:06 42:04 01:10 0:11:34:29 35:18 LCX
11 0:13:58:12 04:22 07:03 24:20 0:13:58:06 58:24 LV
12 0:17:28:06 28:28 29:29 49:02 0:17:22:21 23:10 RCX
13 0:19:48:03 59:26 04:14 19:15 0:19:52:10 53:07 RC
14 0:20:58:05 01:08 02:05 21:12 0:20:54:29 55:20 LCX
15 0:22:08:08 09:02 10:02 29:05 0:22:02:20 03:12 LVX
16 0:24:27:26 39:08 42:21 58:23 0:24:31:17 32:16 RCS
17 0:25:37:26 46:15 50:06 06:03 0:25:38:29 39:26 LV
18 0:26:47:24 47:27 49:05 07:27 0:26:41:05 41:29 RC
19 0:26:47:24 03:17 06:22 23:09 0:26:56:12 57:07 RC
20 0:29:07:20 22:28 26:15 42:19 0:29:15:21 16:16 LC
21 0:31:27:15 46:20 52:08 05:28 0:31:38:04 39:08 RV
22 0:32:37:15 41:21 44:12 01:20 0:32:35:07 35:25 RW
23 0:32:37:15 45:28 51:12 05:07 0:32:38:06 39:01 RC @24
24 0:32:37:15 55:23 58:05 13:14 0:32:44:12 45:23 RV @58
25 0:34:57:12 04:20 07:27 24:10 0:34:57:15 58:09 LC
26 0:36:07:07 11:23 17:16 31:10 0:36:04:10 05:05 RP
27 0:40:47:01 49:28 50:25 10:04 0:40:43:26 44:14 LJX
28 0:41:57:02 06:08 12:28 25:19 0:41:58:02 59:03 RP @8
```

29	0:44:16:27	26:16	30:24	46:07	0:44:19:05	20:01	RC
30	0:44:16:27	30:04	33:07	49:22	0:44:22:20	23:18	LC
31	0:44:16:27	32:27	37:14	52:12	0:44:24:25	25:28	LP @22 changes lanes
32	0:45:26:28	28:25	29:24	49:01	0:45:20:13	21:03	RCX white
33	0:46:36:27	41:20	45:14	01:08	0:46:34:09	35:03	RC
34	0:47:46:22	48:02	48:26	08:09	0:47:42:06	42:22	LCX
35	0:47:46:22	55:22	00:24	15:04	0:47:47:20	48:22	LC
36	0:50:06:21	14:00	18:02	33:20	0:50:06:22	07:16	LW
37	0:50:06:21	19:02	23:07	37:25	0:50:10:01	11:02	LC @36
38	0:51:16:21	28:10	35:02	47:24	0:51:20:19	21:17	LC @10
39	0:53:36:16	38:13	39:09	58:19	0:53:32:14	33:01	LCX
40	0:54:46:16	57:16	02:27	17:02	0:54:49:17	50:20	LW
41	0:55:56:14	58:22	59:18	18:27	0:55:52:18	53:08	LCX
42	0:58:16:09	18:26	19:21	39:03	0:58:12:27	13:15	LCX
43	0:58:16:09	21:24	29:08	41:07	0:58:14:07	15:01	RC
44	0:59:26:07	28:02	28:27	48:09	0:59:22:03	22:21	LC
45	1:00:36:04	50:08	53:14	09:26	1:00:42:15	43:16	LC
46	1:01:46:05	50:18	54:29	10:05	1:01:43:03	44:02	RP @13
47	1:01:46:05	58:14	06:12	17:22	1:01:50:03	51:06	LP @13
48	1:02:56:02	03:02	08:21	22:18	1:02:55:10	56:09	LC
49	1:04:05:28	12:15	15:18	32:09	1:04:05:17	06:09	LC
50	1:05:15:27	16:17	18:08	36:15	1:05:09:25	10:18	RWS J
51	1:05:15:27	19:03	19:28	39:11	1:05:13:07	13:24	LCZ
52	1:05:15:27	27:08	31:04	46:26	1:05:19:23	20:20	LC
53	1:05:15:27	31:22	34:23	51:15	1:05:24:21	25:14	RC
54	1:08:45:21	48:02	48:29	08:10	1:08:42:05	42:22	LVX
55	1:12:15:18	31:15	34:29	51:05	1:12:24:03	25:00	RV dark
56	1:19:15:06	17:09	18:02	37:17	1:19:11:17	12:03	LCX
57	1:19:15:06	19:27	23:27	39:21	1:19:13:03	13:24	RC
58	1:21:35:05	37:06	38:05	57:12	1:21:31:04	31:23	RVX
59	1:21:35:05	39:07	43:00	59:02	1:21:32:14	33:05	LW
60	1:22:45:00	55:27	02:22	15:02	1:22:47:17	48:18	RC @12
61	1:23:55:00	55:18	56:13	15:26	1:23:49:25	50:11	LP
62	1:26:14:28	25:13	28:29	45:03	1:26:18:06	19:01	RV
63	1:27:24:22	32:13	37:10	52:00	1:27:24:21	25:21	LC @8
64	1:29:44:21	47:20	48:13	07:28	1:29:42:00	42:15	RVX
65	1:32:04:12	05:23	06:24	25:25	1:31:59:12	00:03	LCX
66	1:32:04:12	07:09	08:07	27:15	1:32:01:11	01:28	RCX
67	1:35:34:14	44:11	48:11	03:25	1:35:36:13	37:14	LV
68	1:36:44:09	56:26	02:03	16:09	1:36:48:26	49:27	LP
69	1:39:04:06	10:11	13:06		1:39:03:12	04:05	LC
70	1:39:04:06	13:11	17:06		1:39:06:06	07:01	RWS

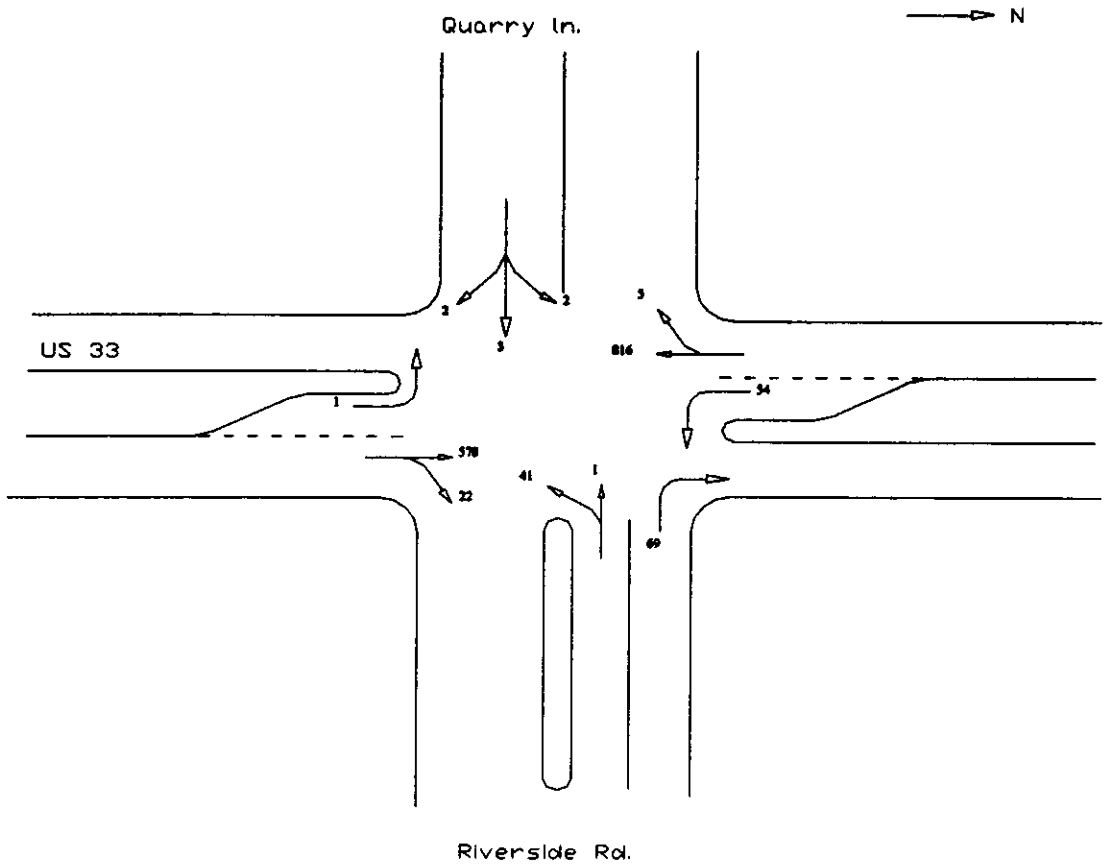
Data reduced from 7-7-97 Tape 2 Cameras 4, 5, 6, by Yizong Cheng 7-21-97.

```
  columns 1-2: label;
  columns 4-13: Camera 5 tape time when the left front wheel
                crosses Cone 6, or the 435 feet line;
  columns 15-19: Camera 5 tape time when the left front wheel
                crosses the 289 feet line;
  columns 21-30: Camera 4 tape time when the left front wheel
                crosses the 545 feet line;
  columns 32-36: Camera 4 tape time when the left front wheel
                crosses Cone 6, or the 435 feet line;
  columns 38-47: Camera 6 tape time when the left front wheel
                crosses Cone 9, or the 1362 feet line;
  columns 49-53: Camera 6 tape time when the left front wheel
                crosses the 1254 feet line;

12345678901234567890123456789012345678901234567890
 1 0:00:19:00 21:11 0:01:10:29 12:24 0:05:53:29 57:05 Cambridge enter
 2 0:00:21:24 24:03 0:01:13:26 15:17 0:06:00:15 02:03
 3 0:02:38:20 42:20 0:03:30:01 32:12 0:08:09:16 13:03
 4 0:03:41:25 43:16 0:04:34:07 35:17 0:09:22:21 24:04
 5 0:04:49:13 51:04 0:05:41:19 43:04 0:10:29:10 30:24
 6 0:04:57:10 59:11 0:05:49:12 51:01 0:10:36:16 38:02
 7 0:06:09:20 11:24 0:07:01:19 03:10 0:11:48:14 50:03
 8 0:06:11:18 13:28 0:07:03:17 05:07 0:11:50:08 51:27
 9 0:09:29:24 31:22 0:10:21:24 23:14 0:15:05:18 08:16 Cambridge enter
10 0:10:39:12 41:12 0:11:31:14 33:05 0:16:16:08 18:06
11 0:13:03:21 05:02 0:13:56:07 57:12 0:18:42:10 45:00 Cambridge enter
12 0:16:27:02 29:07 0:17:19:01 20:24 0:22:04:10 06:04
13 0:18:56:09 58:17 0:19:48:05 49:29 0:24:30:09 33:16 Cambridge enter
14 0:19:59:05 01:09 0:20:51:04 52:29 0:25:35:15 37:11
15 0:21:06:19 08:29 0:21:58:14 00:14 0:26:41:26 44:00
16 0:23:35:14 37:20 0:24:27:13 29:03 0:29:14:04 15:22
17 0:24:43:14 45:06 0:25:35:24 37:07 0:30:23:00 24:17
18 0:25:44:17 47:10 0:26:36:00 38:07 0:31:17:16 19:25
19 0:26:00:18 02:24 0:26:52:16 54:11 0:31:37:27 39:20
20 0:28:20:01 21:29 0:29:22:26 24:28 0:33:59:12 01:00
21 0:30:41:00 43:21 0:31:42:01 43:21 0:36:16:18 18:19
22 0:31:40:02 41:29 0:32:32:04 33:22 0:37:18:03 19:27
23 0:31:42:26 44:27 0:32:34:28 36:17 0:37:21:12 23:02
24 0:31:47:17 50:01 0:32:39:09 41:08 0:37:23:26 25:24
25 0:34:02:05 03:27 0:34:54:12 55:28 0:39:41:08 42:27
26 0:35:07:27 10:09 0:35:59:12 01:17 0:40:41:15 43:27
27 0:39:48:14 50:12 0:40:40:17 42:08 0:45:26:06 28:02
28 0:41:01:29 04:02 0:41:53:26 55:20 0:46:33:25 37:23 Cambridge enter
29 0:43:23:06 25:12 0:44:15:03 16:27 0:48:58:04 01:01 Cambridge enter
30 0:43:26:11 28:16 0:44:18:14 20:05 0:49:04:19 06:10
31 0:43:28:06 30:20 0:44:21:05 22:29 0:49:05:15 07:10
32 0:44:24:17 26:26 0:45       33:00                  Side enter
33 0:45:38:28 41:00 0:46:30:29 32:19 0:51:16:13 18:08 changes lanes
34 0:46:47:05 48:29 0:47:39:12 40:28 0:52:26:06 27:24
35 0:46:51:27 53:24 0:47:44:03 45:20 0:52:30:07 39:27 brakes at 1300', sees police
36 0:49:11:07 13:02 0:50:03:13 05:01 0:54:49:28 51:16
37 0:49:14:00 15:29 0:50:06:08 07:23 0:54:54:02 55:15
38 0:50:24:21 26:23 0:51:16:23 18:15 0:56:02:04 03:26
39 0:52:37:06 39:06 0:53:29:09 31:00 0:58:15:01 16:23
40 0:53:53:00 55:04 0:54:45:04 46:25 0:59:31:00 32:21
41 0:54:57:00 58:29 0:55:49:01 50:24 1:00:34:17 36:12
42 0:57:17:19 19:15 0:58:09:24 11:12 1:02:55:15 57:13 changes lanes
43 0:57:17:19 20:11 0:58:09:05 11:10 1:02:51:28 54:02
44 0:58:25:03 28:09 0:59       19:09                  Side enter
45 0:59:45:21 48:03 1:00:37:18 39:16 1:05:22:22 24:19
46 1:00:45:25 48:19 1:01:37:05 39:16 1:06:17:12 19:25
47 1:00:53:13 55:22 1:01:45:10 47:07 1:06:30:08 32:05
48 1:01:59:10 01:14 1:02:51:07 53:04 1:07:33:02 36:10 Cambridge enter
49 1:03:10:07 12:00 1:04:02:16 04:01 1:08:49:16 51:04
```

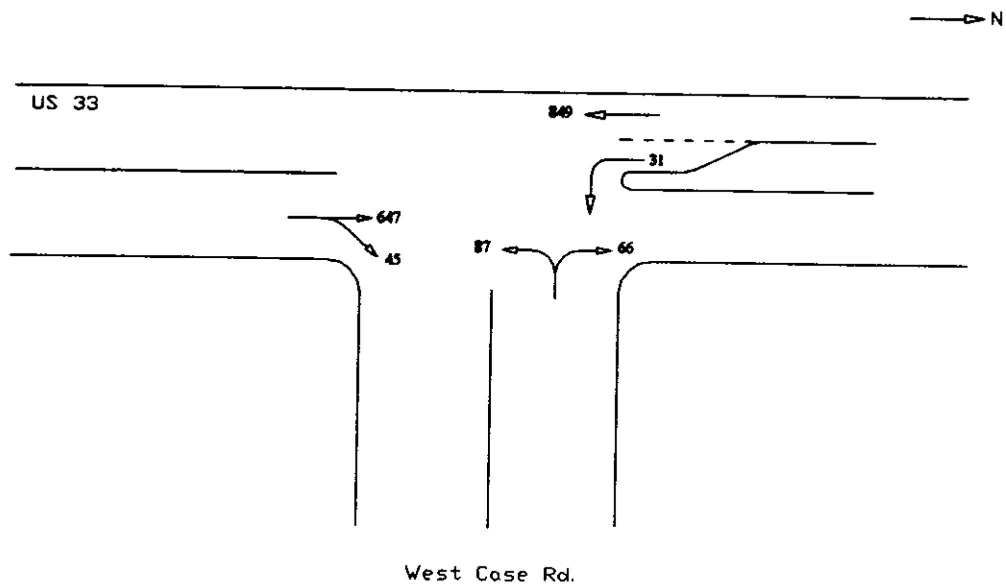
50	1:04:14:06	16:07	1:05:06:14	08:01	1:09:53:21	55:06	Cambridge enter, changes lanes
51	1:04:18:00	19:25	1:05:10:04	11:24	1:09:56:14	58:04	
52	1:04:23:17	25:19	1:05:15:19	17:11	1:09:59:17	02:12	Cambridge enter
53	1:04:29:10	31:07	1:05:21:19	23:02	1:10:09:10	10:27	
54	1:07:46:27	48:23	1:08:39:03	40:21	1:13:25:03	26:23	
55	1:11:32:23	35:17	1:12:24:07	26:15	1:17:01:10	04:25	Cambridge enter
56	1:18:16:20	18:09	1:19:09:00	10:14	1:23:56:05	57:20	
57	1:18:17:23	19:21	1:19:09:21	11:13	1:23:56:00	57:19	
58	1:20:35:20	37:22	1:21:27:21	29:11	1:26:13:14	15:03	
59	1:20:36:28	38:26	1:21:29:01	30:22	1:26:14:14	16:07	
60	1:21:51:02	53:12	1:22:43:00	44:44	1:27:28:17	30:08	
61	1:22:54:25	56:21	1:23:47:03	48:19	1:28:30:17	33:16	Cambridge enter
62	1:25:22:16	24:14	1:26:14:19	16:09	1:31:01:14	03:03	
63	1:26:26:11	30:02	1:27	20:23			Side enter
64	1:28:47:06	48:29	1:29:39:14	40:27	1:34:26:21	28:11	
65	1:31:03:03	05:11	1:31:55:03	56:29	1:36:36:27	40:09	
66	1:31:06:03	08:02	1:31:58:06	59:25	1:36:44:01	45:23	
67	1:34:39:29	42:04	1:35:32:01	33:24	1:40:13:24	16:28	Cambridge enter
68	1:35:52:05	54:15	1:36:44:05	46:00	1:41:31:21	36:02	Cambridge enter
69	1:38:08:06	09:27	1:39:00:15	01:29	1:43:47:16	49:05	
70	1:38:10:14	12:15	1:39:02:18	04:07	1:43:49:17	51:05	

US 33 and Riverside Green Road

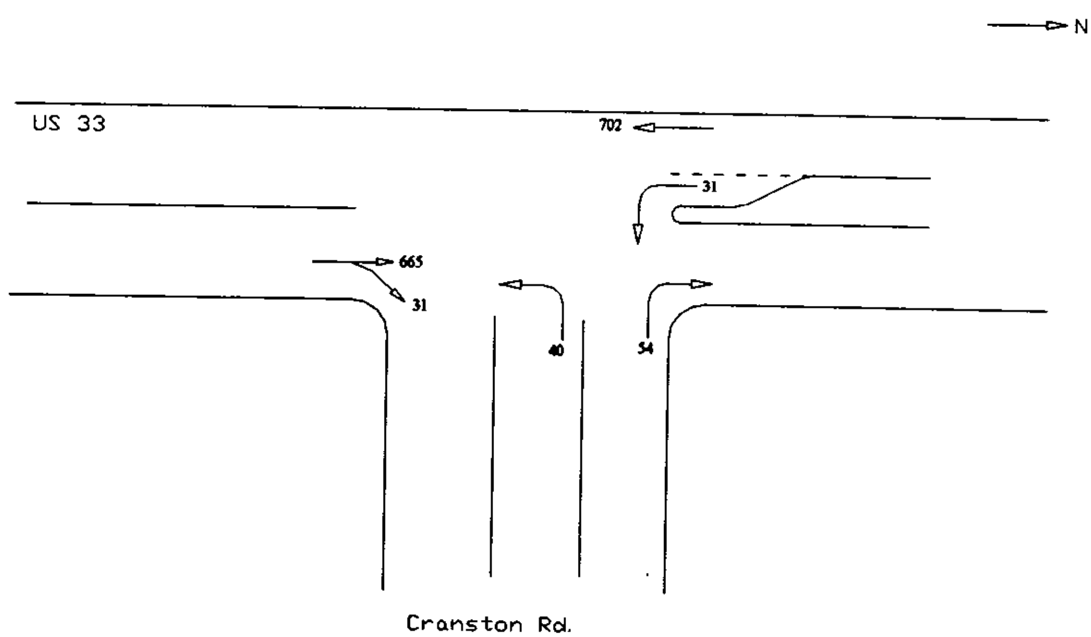


Word Searchable Version not a True Copy

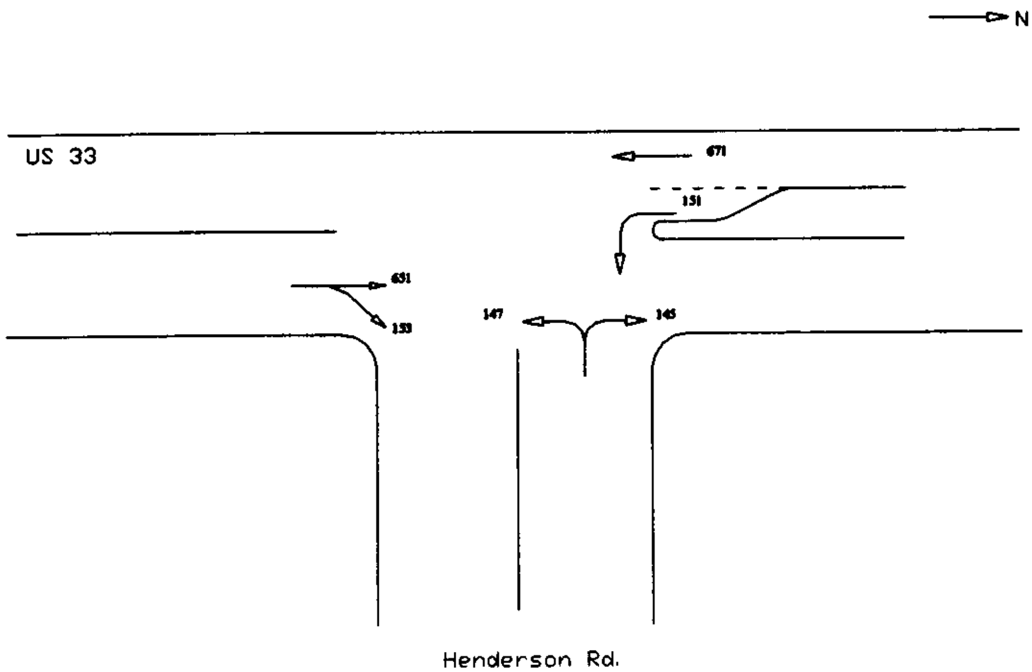
WestCase Road and US 33



Cranston Road and US 33



Henderson Road and US 33



Hayden Road and US 33