Measuring the response of drivers to a yellow phase with a video based approach

Yue Liu[1], Gang-Len Chang[1], Ruihua Tao[2], Eric Tabacek[2], and Thomas Hicks[2]

[1]Department of Civil Engineering, University of Maryland at College Park, College Park, MD 20742; PH (301) 405-1953; FAX (301) 405-1235; email: troybest@umd.edu
[2]Office of Traffic and Safety, Maryland State Highway Administration, 7491 Connelley Drive, Hanover, MD 21076; PH (410) 787-5860; FAX (410) 582-9469; email: rtao@sha.state.md.us

Abstract: Understanding the response and acceleration/deceleration rate of driving populations to a yellow phase is essential for estimating the dynamic distribution of intersection dilemma zones. This paper presents a video-based method for measuring driver responses during a yellow phase, including their speed evolution profile, acceleration/deceleration rate, and the approximate reaction time. Such information is critical for understanding the spatial distribution of dynamic dilemma zones and the design of strategies to improve intersection safety. This paper details the key components of the proposed system and the systematic procedures for both field operations and data extraction. The results of a rigorous validation with an advanced experimental vehicle provided by Nissan are also reported in this paper.

Background

A reliable measurement of the speed evolution profile of driving populations from the start of a yellow phase to the red phase can offer invaluable information for understanding behavior patterns of drivers and the design of safety-improvement strategies. A well-captured speed profile can directly yield the following data for estimating the distribution of dynamic dilemma zones: 1. Measuring a driver's response time to the yellow phase; 2. Classifying drivers into different groups, based on their acceleration/deceleration patterns, and reaction times; 3. Developing a statistical model for estimating the spatial distribution of dynamic dilemma zones at signalized intersections; 4. Analyzing the car-following behavior of drivers during a yellow phase; 5. Investigating the interrelations between various driver responses, yellow phase design, and signal related crash rates.

A variety of sensors have been used in practice for direct measurement of vehicular speed, including microwave sensors, radio wave sensors, ultrasonic sensors, radar speed meters, and infrared speed meters. However, all these sensors are for direct measurement of a spot speed, which cannot reliably track an individual vehicle's movement over a target interval. Other direct speed measurement methods, such as distance-measuring instrument (DMI), global positioning systems (GPS), and cellular-phone location systems, have also been used to obtain the speed data along a roadway segment. But these methods can only capture the speed evolution of vehicles equipped with those measurement systems, which are likely to yield only biased and limited samples for analysis. One of the alternative methods is to measure a vehicle's speed indirectly from video images. A large body of methods for indirect speed measurements is available in the literature and has been used in practice. Such methods often involve quite costly and complex image processing work in spatial dimension, including identifying, extracting, and tracking vehicle for computing the speed. A relative cost-effective way to measure a vehicle's speed, as reported in the literature, is to employ video cameras or camcorders. This approach often requires setting a speed trap at the video image with two reference lines separated by a known distance (Robertson, D. 2000; Dickinson et al. 1984; Ashworth et al. 1985). One can then compute the average speed between these two reference lines by dividing the distance with the travel time. This study intends to extend these video-based methods for spot speed measurements to a reliable and cost-effective system for measuring the spatial evolution of vehicle speeds. The key idea of the proposed approach is to superimpose reference lines over the video image and measure the vehicle's travel times between these lines sequentially to obtain the speed evolution profile. The distance between two adjacent reference lines is optimized to minimize the potential measurement errors under given operational conditions. The time when vehicles reach the reference line and the starting time of a yellow phase are also recorded by the program for extraction of speed evolution profile before-and-after a yellow phase.

System Components

The entire system for speed measurement includes the following components: 1. One DVD video camera, which can record at variable time-elapse rates up to 30 frames per second, along with several re-writable DVD video disks; 2. One adjustable tripod to allow a flexible camera orientation setup; 3. Orange cones placed at an identical distance along the roadway as reference points for video benchmarking and reference line generation; 4. A frame-by frame video editing computer program, which must be able to read the video file directly from the videodisk without any converting or capturing job, superimpose the reference lines onto the video image, slice the video footage into a small set of segments (up to a frame) to facilitate accurate analysis, and record the necessary timestamps when vehicles touch the line.

Implementation Issues

With the system developed for this study, several critical issues need to be addressed, including camera set-up, measurement accuracy, selection of speed trap length, video benchmarking, reference line generation, and data extraction.

Camera Set-up

The far-side camera should be set up based on the following criteria (see Figure 1): 1. The entire survey segment can be captured as long as necessary; 2. The signal phase changes can be captured; 3. The front wheel of vehicles can be identified as the detection point; 4. All the orange cones can be observed clearly in the video image.

Measurement Accuracy Analysis

According to the measuring approach, the average speed over each trap length is approximated as the spot speed at the reference line, there inevitably exists some difference from the actual spot speed. Therefore, if the trap length is sufficiently small and the vehicle keeps constant speed within the trap, the average speed will be equal to its spot speed, and there will be no error associated with the above conversion. So the length of the speed trap should be set as short as possible to reduce the approximation errors. On the other hand, the length of the trap should be maximized to reduce the time-elapse errors caused by a video camera. Hence, there exists a trade-off between conversion errors and time-elapse errors in setting the speed trap length. Note that vehicles traveling within the trap may execute different acceleration or deceleration rates. In this study, we use the worst scenario to assess the maximal possible measurement errors. For the speed conversion errors, the worst scenario occurs when a vehicle keeps accelerating or decelerating within a trap using the maximum acceleration rate ($16.0 ft/\sec^2$) or deceleration rate ($-11.2 ft/\sec^2$) (Gazis, D. 1960). For the time-elapse error, the worst scenario occurs if one frame of time is missing or over-counting from the calculation of travel time between two reference lines. The maximal possible error estimation models are approximated with the following equations:

$$\varepsilon_{\max}^{c} = \frac{\left| v_{act} - \sqrt{v_{act}^{2} - \frac{2aD}{(1.47)^{2}}} \right|}{2} \qquad (1)$$

$$\varepsilon_{\max}^{t} = \frac{v_{act}^{2}}{K(v_{act} - \sqrt{v_{act}^{2} - \frac{2aD}{(1.47)^{2}}}) + v_{act}} \qquad (2)$$

Where: $\varepsilon_{\max}^{c}$ is the maximal speed conversion error (mph); $\varepsilon_{\max}^{t}$ is the maximal time-elapse error (mph); v_{act} is the actual speed of a vehicle at the reference line (mph); K is the number of frames per second; D is the length of the speed trap (ft); a is the maximal acceleration/deceleration rate (absolute values are used) within the speed trap ($ft/\sec^{2}$).

The above estimation models are deducted from basic vehicle moving dynamics and the acceleration/deceleration rates used are absolute values. The estimation model is somewhat conservative as vehicles don't often use the maximal acceleration/deceleration rate within a speed trap, and the missing or over-counting time from the calculation of travel time is always a fraction of one frame. The error estimation equations show that $\varepsilon_{\max}^{c}$ increases with length of a speed trap, and $\varepsilon_{\max}^{t}$ decreases with an increase in the speed trap length.

Selection of Speed Trap Length

Although it is difficult to compute a theoretically optimized value, this study has taken into account both types of errors and their trade-off in setting the speed trap length. It can be easily seen that an effective speed trap length shall lie at the point where $\varepsilon_{\max}^{c} = \varepsilon_{\max}^{t}$, so as to minimize and balance both types of errors. The speed trap lengths and the measurement errors under different speed levels can then be computed by the above equality. For each survey location, the average speed of the survey segment is used to decide which speed trap length should be used, and the selected speed trap length will then be applied in video benchmarking and speed data extraction, as summarized in Table 1.

Video Benchmarking and Reference Line Generation

The purpose of this task is to extract the spatial information of the target survey segment, and generate virtual reference lines at the video image where cones could not be used as reference points. The study has developed the following procedures (see Figure 2 and 3): 1. Take sample digital photos from different camera orientations during the field survey. 2. Mark grid corners at each video image to construct the coordinate systems. 3. Mark corresponding locators (the same object at different images, here the cone's vertex is used as the corresponding locator) for calibration. 4. Calibrate camera parameters and model the coordinate system. 5. Use the calibrated information for reference point extraction on the image. 6. Superimpose the extracted points over the video image to generate reference lines for speed measurements.

Data Extraction

Given the above procedures finished and survey videos available, a computer program was used to extract speed evolution data, as shown in Figure 4. During the extraction process, for each cycle, record the yellow phase starting and ending time separately, and identify all the through vehicles trapped in the yellow phase. For each vehicle, record the time when it travels over each speed trap. Calculate each vehicle's speed evolution from the elapsed time and the distance traveled.

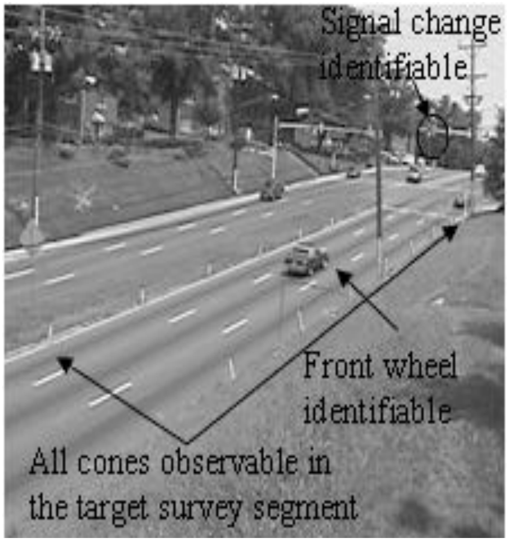

Figure 1. Camera set-up

Table 1. Selected speed trap lengths and maximal measurement errors

Speed[1] (mph)	Selected Speed Trap Length (ft)	Maximal Speed Conversion Error (mph)	Maximal Time-elapse Error (mph)
10	10[2]	2.89	0.76
15	10[2]	2.17	1.33
20	12	1.95	1.95
25	15	2.19	2.19
30	20	2.36	2.36
35	25	2.56	2.56
40	30	2.77	2.77
45	35	2.85	2.85
50	43	2.90	2.90
55	49	3.13	3.13
60	55	3.37	3.37

[1] The speed in the table is the average speed at the target survey segment.

[2] The length of 10 ft was set as minimum speed trap length for operational convenience.

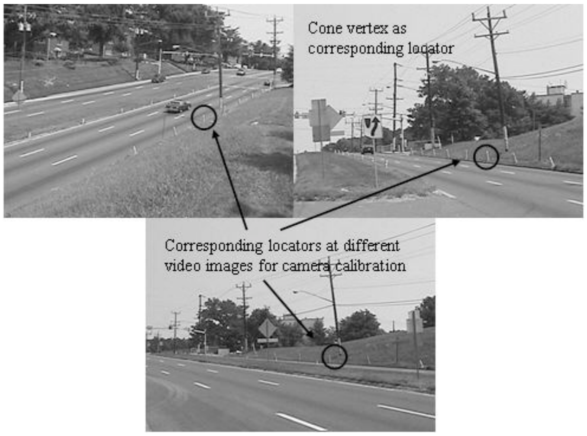

Figure 2. Camera calibration

Figure 3. Extracted reference points

Field Validation

To evaluate the accuracy of the proposed system for speed measurements, this study has conducted a field test at the intersection of MD 650 and Metzerott Rd (at northbound approach with an average speed about 40 mph). A Nissan Infinity Q45 instrumented with a CAN (Controller Area Network) message converter was employed in the test to provide the true speeds for comparison (the differences between video measured speeds and those from CAN were considered as errors). The CAN message converter is a measuring device which can convert the actual speed messages of the vehicle to decimal values. It was calibrated to the precision of ±0.0001 mph and connected to a laptop computer via a serial cable to display the speed of the experimental vehicle in a time frame of every 0.01 second. Two video cameras were used for validation. One was set at the far side to record the movements of the experimental vehicle in the surveyed segment, and the other was installed in the vehicle to record its actual speed displayed on the screen of the laptop. The synchronization of these two video cameras has yielded the consistency between the accurate speed by CAN and the measured speed by video using the timestamp information (see Figure 5). Based on the above speed trap length selection design, the speed trap was set at 30 ft to minimize possibly maximal approximation and/or time-elapse errors. The field validation consists of 24 trials through the test site with entry speeds at six different levels (20-25, 25-30, 30-35, 35-40, 40-45, 45-50 mph), and each speed level has 4 trials (2 for pass, 2 for stop). There are a total of 180 speed records (each “pass” trial has 8 records and each “stop” trial has 7 records through the evolution process to the stop-line) for validation. The errors of speed measurements were calculated for each experiment and displayed in Table 2.

Figure 4. Data extraction

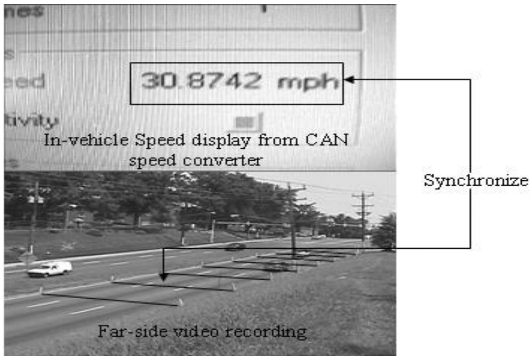

Figure 5. Field validation

Table 2. Errors of the Video-based Method under Different Entry Speeds

Entry speed level[1] (mph)		Speed Range[2] (mph)	Mean Error[3] (mph)	(Min, Max) Error[3] (mph)	Maximal Theoretical Error[4] (mph)
20-25	P	(20-32)	0.99	(0.01,3.59)	4.55 (>3.59)
	S	(0-26)	1.33	(0.04,3.68)	6.69 (>3.68)
25-30	P	(17-30)	1.22	(0.04,2.58)	5.45 (>2.58)
	S	(0-30)	1.57	(0.04,3.99)	6.69 (>3.99)
30-35	P	(32-39)	1.61	(0.17,3.56)	3.65 (>3.56)
	S	(0-34)	1.79	(0.00,3.77)	6.69 (>3.77)
35-40	P	(33-47)	0.75	(0.01,1.95)	4.08 (>1.95)
	S	(0-39)	1.87	(0.27,4.14)	6.69 (>4.14)
40-45	P	(41-50)	0.71	(0.01,3.18)	4.08 (>3.18)
	S	(0-43)	1.62	(0.11,3.86)	6.69 (>3.86)
45-50	P	(42-50)	1.26	(0.09,3.05)	4.08 (>3.05)
	S	(0-48)	1.61	(0.32,3.54)	6.69 (>3.54)
Sum	P	/	1.09	(0.01,3.59)	5.45 (>3.59)
	S	/	1.53	(0.00,4.14)	6.69 (>4.14)

[1] The entry speed is a spot speed when the test vehicle enters the survey segment.

[2] Speed range means speed evolution range.

[3] All the errors in the table are absolute errors.

[4] The maximal theoretical errors were the maximal of values computed by Eq. (1) and (2) given the speed trap length of 30 ft.

The maximum and minimum absolute values of the errors for the experiments and the maximum theoretical errors given by the Equations (1) and (2) were also listed. It is obvious that the errors of the speed measurements were less than the maximum theoretical errors, which suggests that the methodology developed in the study is sufficiently reliable for estimating the speed evolution. In Table 2, it is noticeable that across all the six levels of entry speeds, the experiments with “stop” maneuvers produced relatively larger measurement errors than with “pass” operations, which suggests that the accuracy level of speed measurements be sensitive to the acceleration/deceleration rate. The reason is that the length of the speed trap was set at 30ft on the basis of the speed level of 40-45 mph to minimize the potential measurement errors. However, when the vehicle’s speed diverted away from that speed level, the measurement errors may increase and the preset speed trap length may not be the most effective selection. The way to improve accuracy of speed measurements for “stop” maneuvers is to use a best-fit-in length of speed traps, based on speed changes. However, it remains to be a challenge in practice.

Measuring the Response of Drivers

A driver's perception-reaction time in response to YELLOW is a critical factor that affects the dilemma zone distribution at signalized intersections (Xiang et al. 2005). Field measurements of a driver's perception-reaction time can offer invaluable information for understanding the interrelationship between driver behavior and surrounding factors. The proposed method offers a convenient way to approximate a driver's response time with his/her speed profile (approximately equal to a theoretical perception-reaction time). Figure 6 shows a speed evolution of a stop-maneuvered case in the field validation. A yellow phase started at the timestamp of 1164.01584 seconds. After that a significant speed reduction (10.43 mph) occurred between the timestamps of 1164.70886 and 1165.21386, as shown in Figure 6. Despite the average speed measurement error of ±1.53 mph for "stop" cases (see Table 2), the speed change in this case was still significant in such a short time period. Therefore, this speed reduction was identified as the driver's response to YELLOW, and the driver's response time was then estimated to lie between 0.69 and 1.20 seconds. One may use the average to represent the approximate response time of a driving population.

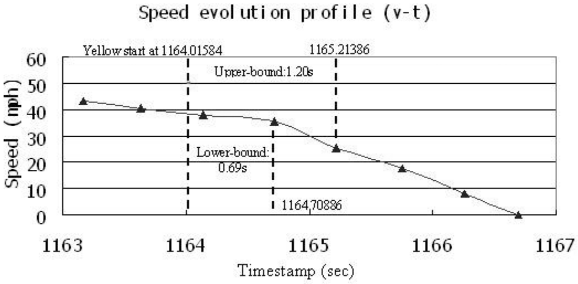

Figure 6. Measuring driver's response

Conclusion

It is found that the accuracy level of speed measurements by a video-based method is a function of several factors, such as length of the speed trap, the acceleration/deceleration rates and speed within the speed trap, time-elapse rate used and camera setup. Test results show that, if properly designed, the proposed video-based method is effective to measure the speed evolution, the acceleration/deceleration rate changes, and the response time of different driving populations to YELLOW, which provide all essential information for understanding the spatial distribution of dilemma zones.

References

Ashworth, R., D.G. Darkin, (1985) "Applications of Video Image Processing for Traffic Control Systems." Second International Conference on Road Traffic Control, London, UK, pp. 119-122.

Dickinson, K.W. and R.C. Waterfall. (1984). "Video Image Processing for Monitoring Road Traffic." IEEE International Conference on Road Traffic Data Collection, pp. 105-109.

Gazis, D., Herman, R., and Maradudin, A. (1960). "The problem of the amber signal light in traffic flow." *Operations Research*, Vol. 8, No. 1, pp. 112-132.

Robertson, D. (2000). "Spot Speed Studies." *Manual of Transportation Engineering Studies*, ITE, Washington, D.C., pp.33-51

Xiang, H., C.S. Chou, G.L. Chang, and R. Tao. (2005) "Observations and classification of Drivers Responses during Yellow-Light Signal Phase." Presented at 84th Annual Meeting of Transportation Research Board, Washington DC.