A Video-base System for Measuring Dynamic Dilemma Zones at Signalized Intersections

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Abstract—**This paper presents a video-based system for measuring dynamic dilemma zones at signalized intersections. The proposed system is cost-effective and sufficiently reliable for measuring various critical information associated driver behavior, including the speed before-and-after the yellow phase, the acceleration/deceleration rates and the approximate reaction time to an encountered yellow phase, and differences in driving patterns. 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 field operations, data extraction, and system validation. The estimation of dilemma zones based on 1123 field observations of drivers' responses via the proposed system at six intersections of high accident frequency are also reported in this paper.**

I. INTRODUCTION

UNDERSTANDING the distribution of dynamic dilemma zones during the yellow phase is one of the essential tasks in contending with traffic safety related issues at signalized intersections. To capture the distribution of dilemma zones, the following key information should be collected:

- *Acceleration/deceleration rates of drivers before and after a yellow phase;*
- *Distance and expected time to the stop-line when drivers perceive the commencement of a yellow phase;*
- *The speed distribution of different driving populations in response to a yellow phase.*

A reliable measurement of the speed evolution profile of driving populations (see Fig. 1) from the commence of a yellow phase to the red phase can offer the above required invaluable information for understanding the dynamic nature of dilemma zones and design of safety-improvement strategies. In order to measure the above information reliably, this study has developed a video-based data collection system, as shown in Fig. 2, which has the following functions:

- *Precisely tracking each individual vehicle trapped in the yellow phase;*
- *Computing the exact distance and time for a vehicle to reach the stop-line from the start of a yellow phase;*
- *Measuring the speed evolution without influencing the behavior of drivers during a yellow phase;*

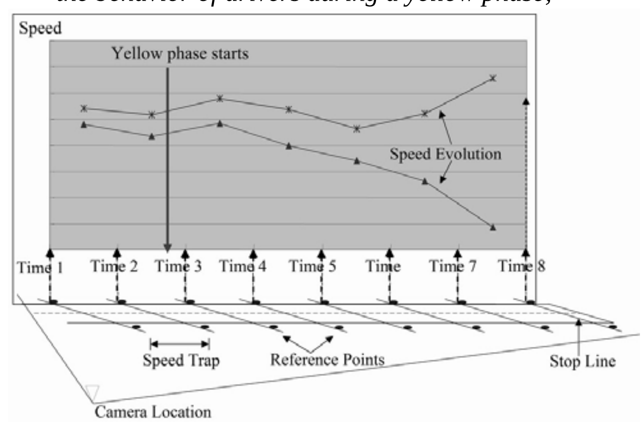

Fig. 1. Vehicular speed evolution profile

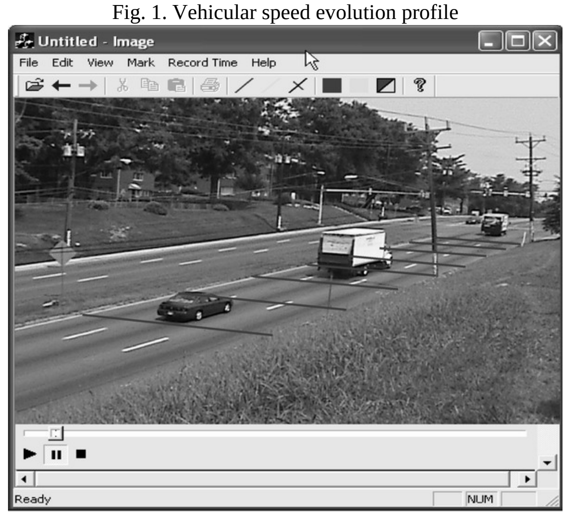

Fig. 2. The video-based measuring system

A large body of systems 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 [1][2][3][7][8]. One can then compute the

Manuscript received April 25, 2007.

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average speed between these two reference lines by dividing the distance with the travel time. However, none of the above methods have been fine-tuned to be applied to collect the critical information required in measuring the distribution of dilemma zones at signalized intersections. 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, from which, the dilemma zone distribution can be obtained indirectly. The key idea of the proposed system is to superimpose reference lines over the video image and measure a vehicle's travel times between these lines sequentially to obtain the speed evolution profile. The distance between two adjacent reference lines (i.e., speed trap length) has been optimized to minimize the potential measurement errors under given operational conditions [5]. One can superimpose reference lines over the video image through a specially-designed computer program. 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 the speed evolution profile before-and-after a yellow phase. Fig. 3 illustrates the entire operational procedures with the proposed measuring system.

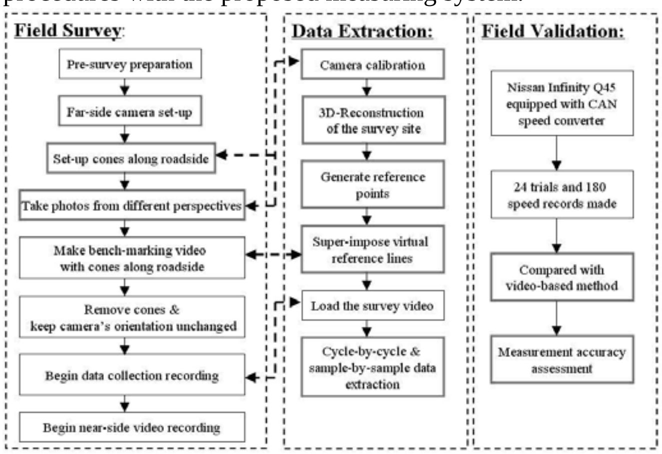


Fig. 3. Operational procedures of the video-based measuring system

II. SYSTEM DETAILS AND IMPLEMETATION PROCEDURES

A. System Components

The entire system for speed measurement includes the following components:

- *One DVD video camera, which can record at variable time-elapse rates up to 30 frames per second, and monitor the roadway segment to get samples trapped in the a yellow phase;*
- *Several re-writable DVD video disks, to facilitate the computer operations and to save the video tape conversion time;*
- *An adjustable tripod to allow a flexible camera orientation setup;*
- *Orange cones placed at an identical distance along the roadway as reference points for camera calibration and video benchmarking;*
- *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 future analysis;
  - Record the necessary timestamps.

B. Field Survey Procedures

To collect the field video data at the target level of quality, this study has developed the following systematic procedures for field surveys:

- *Step 1: Pre-survey preparations, including:*
  - Re-charging the camera and formatting video disks;
  - Measuring the average speed of vehicles at the survey location for system placement and operations.
- *Step 2: Determine the far-side camera location and set it up according to the following criteria (see Fig. 4):*
  - The entire survey segment can be captured as long as necessary;
  - The signal phase changes can be captured;
  - The front wheel of vehicles can be identified as the detection point;
  - All the orange cones can be observed clearly in the video image.

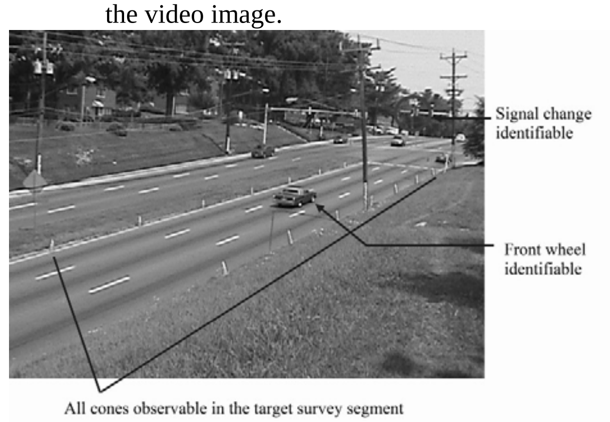


Fig. 4. Far-side camera set-up

- *Step 3: Set the video camera at* $K = 30$ *frames per second, and use the high-quality mode to ensure the time when a vehicle's front wheel breaks the reference lines can be clearly identified.*
- *Step 4: Set up the orange cones along both sides of the target survey segment at an identical distance [5], and these cones' locations will then be used as reference points for camera calibration (see Fig. 5).*
- *Step 5: Take three digital photos on the survey segment with the placement of those cones from*

different perspectives for later camera calibration (see Fig. 5).

- *Step 6: Start the video recording with all the orange cones remaining at the survey segment for 30 seconds, and then make it as a benchmarking video (see Fig. 6a).*

Fig. 5. Camera calibration

- *Step 7: Keep the position and orientation of the camera unchanged to make sure that the data collection video could be used without any offsetting or shifting from the benchmarking video, and then remove all the orange cones to avoid influencing the behavior of drivers (see Fig. 6b).*
- *Step 8: Perform the data collection video recording, and change disks when necessary.*
- *Step 9: Finish recording and save all information into a DVD disk for future data extraction.*

C. Data Extraction Procedures

Given the field recorded videos, this study has developed the following procedures for extracting speed evolution data:

- *Step 1: Perform camera calibration and image measuring through those three digital pictures taken prior to the field survey, and generate virtual points where cones could not be used as reference points due to impedance.*
- *Step 2: Load the benchmarking video first with the editing computer program, and then superimpose the reference lines of each speed trap over the video image, based on the location of orange cones or those virtual points.*
- *Step 3: Save the location of reference lines, and keep them superimposed over the video image and unload the benchmarking video.*
- *Step 4: Load the survey video and keep those reference lines at the same locations in the video image (see Fig. 6b).*
- *Step5: For each cycle, record the yellow phase starting and ending time separately, and identify all the through vehicles trapped in the yellow phase.*
- *Step 6: For each vehicle, record the time when it travels over each speed trap.*
- *Step 7: Calculate each vehicle's speed evolution from the elapsed time and the distance traveled.*

D. Camera Calibration and Virtual Reference Points Generation

The purpose of this task is to extract the spatial information of the target survey segment, and generate virtual points at the video image where cones could not be used as reference points. The study has developed the following procedures (see Fig. 5):

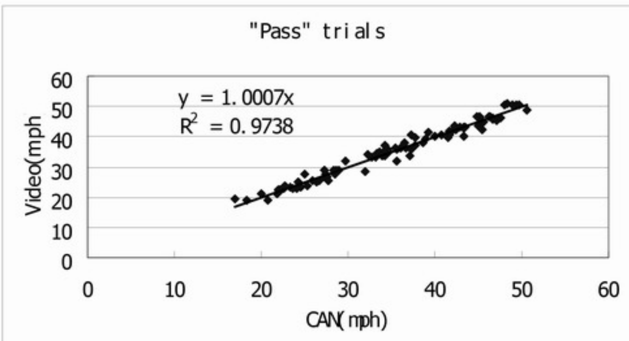
- *Step 1: Sample images from different camera orientations during the field survey procedures.*
- *Step 2: Mark grid corners at each video image to construct the coordinate systems.*
- *Step 3: Mark corresponding locators (the same object at different images, here the cone's vertex is used as the corresponding locator) for calibration.*
- *Step 4: Calibrate camera parameters and model the coordinate system.*
- *Step 5: Use the calibrated information for virtual points extraction on the image.*
- *Step 6: Superimpose the extracted points over the video image to replace the cones as reference points for speed measurements.*

Fig. 6a. Benchmarking with cones or reference points

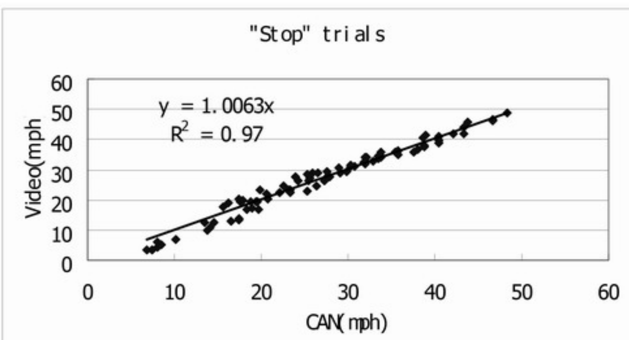
Fig. 6b. Data collection without cones to avoid influencing driver's behavior

III. SYSTEM VALIDATION

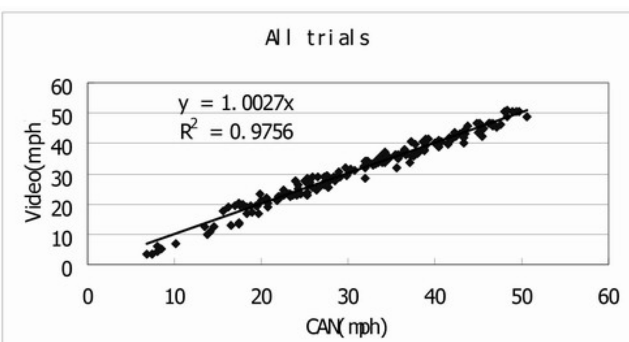
To evaluate the accuracy of the proposed system for speed measurements, this study has also conducted a field test at the intersection of MD 650 and Metzerott Road with a Nissan Infinity Q45 instrumented with a CAN message converter. The CAN message converter is a measuring device which can convert the actual speed to the precision of ±0.0001 mph, and one can connect it 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. The speed data from the CAN message converter are deemed as the "true" speed, and used as the basis for evaluating the accuracy of the data collected from the proposed video-based system.



a.



b.



c.

Fig. 7. Speed measurements by video versus the CAN converter

The field validation consists of 24 trials over the test site with six different entry speeds (20-25, 25-30, 30-35, 35-40, 40-45, 45-50 mph), and 4 trials (2 for pass, 2 for stop) for each speed level. There are a total of 180 speed records ("pass" plus "stop" records) for the system validation. As shown in Fig. 7, there exists a high correlation between the measured speeds and the actual speeds (by CAN), which indicates a high accuracy of those speeds measured with the developed video-based method.

IV. MEASURING DILEMMA ZONES

This study has collected a total of 1,123 observations of individual driver responses over the yellow phase with the aforementioned video-based measuring system. Since driver behavior and characteristics at signalized intersections are not uniformly distributed, the distribution of the dilemma zones also varies with different driving populations [9]. For better understanding the dynamic nature of dilemma zones and their variation, this study has first classified the driving population at each sample intersection into three distinct groups: "aggressive pass" (A-Pass), "conservative stop" (C-Stop), and "normal pass or stop" (Normal), based on their response to a yellow phase [6], and then measuring their key characteristics via the proposed system, such as the approaching speed and distance to stop-line when the yellow phase starts, average acceleration/deceleration rates after the yellow phase, and their approximate perception-reaction times.

With the above critical behavioral information, the dilemma zone distribution for each driving group is estimated with the following equation recommended by ITE [4] at each target intersection:

$$x_{dz} = x_c - x_0 = v_0\delta_2 + \frac{v_0^2}{2a_2} - v_0\tau + (w+L) - \frac{1}{2}a_1(\tau-\delta_1)^2$$

where:

$x_c =$ the critical distance for a smooth "stop" under the maximum deceleration rate;

$x_0 =$ the critical distance for "pass" under the maximum acceleration rate;

$\tau =$ duration of the yellow phase (sec);

$\delta_1 =$ reaction time-lag of the driver-vehicle complex (sec);

$\delta_2 =$ decision-making time of a driver (sec);

$v_0 =$ approaching speed of vehicles (ft/sec);

$a_1 =$ vehicle acceleration rate (ft/s^2);

$a_2 =$ vehicle deceleration rate (ft/s^2);

$w =$ intersection width (ft); and

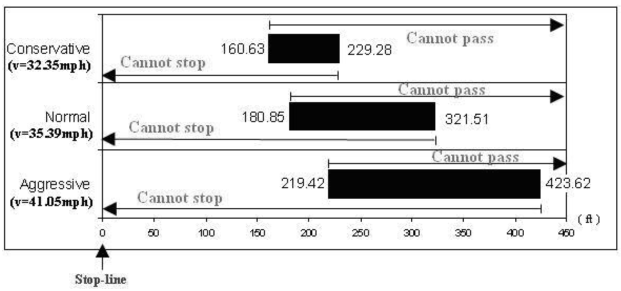
$L =$ average vehicle length (ft).

Those parameter values used for computing the dilemma zones at all observed intersections are summarized in Table 1, and the results of the dilemma zone distributions are shown in Fig. 8, from which we can observe that, based on the field measured parameter values from the proposed video-based system, the length and the location of the dilemma zones vary with the speed of the approaching vehicles, driver reaction times, and vehicle acceleration/deceleration rates of different driving populations, and there exists significant differences between the theoretically assumed and the actual distributed dilemma zones.

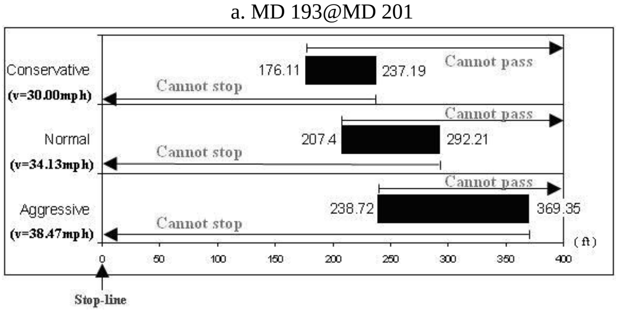
TABLE I

PARAMETER VALUES FOR COMPUTING THE DILEMMA ZONES

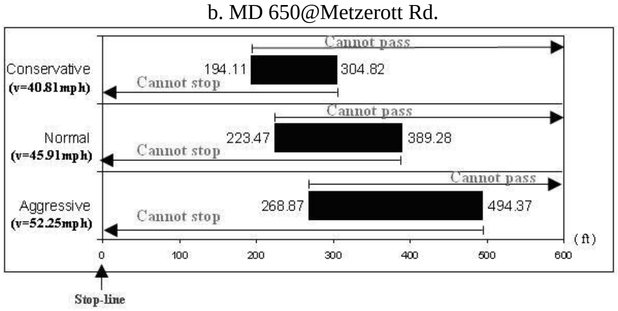
Surveyed Intersections	Group	a_1 (ft/sec^2)	a_2 (ft/sec^2)	v_0 (mph)	τ (sec)	w (ft)	L (ft)	δ_1 (sec)	δ_2 (sec)
193@201	A-Pass	0.39	-4.93	41.05			12	0.93	0.93
	Nomal	0.20	-4.93	35.39	4.5	42	12	0.93	0.93
	C-Stop	0.20	-6.46	32.35			12	1.16	1.16
650@Metzrott	A-Pass	0.80	-5.10	38.74			12	0.93	0.93
	Nomal	1.10	-5.10	34.13	5	40	12	0.93	0.93
	C-Stop	1.10	-5.20	30.00			12	1.16	1.16
Randolph@Glennian	A-Pass	0.92	-6.94	52.25			12	0.93	0.93
	Nomal	-0.82	-6.94	45.91	4	30	12	0.93	0.93
	C-Stop	-0.82	-7.61	40.81			12	1.16	1.16
410@Belcrest	A-Pass	2.66	-4.17	38.09			12	0.93	0.93
	Nomal	1.10	-4.17	31.19	4.5	84	12	0.93	0.93
	C-Stop	1.10	-4.22	29.55			12	1.16	1.16
410@Adelphi	A-Pass	0.69	-4.30	38.70			12	0.93	0.93
	Nomal	-0.28	-4.30	30.49	5	87	12	0.93	0.93
	C-Stop	-0.28	-5.40	27.21			12	1.16	1.16
193@Mission	A-Pass	1.33	-5.87	54.40			12	0.93	0.93
	Nomal	1.00	-5.87	44.15	5.5	56	12	0.93	0.93
	C-Stop	1.00	-8.24	41.00			12	1.16	1.16



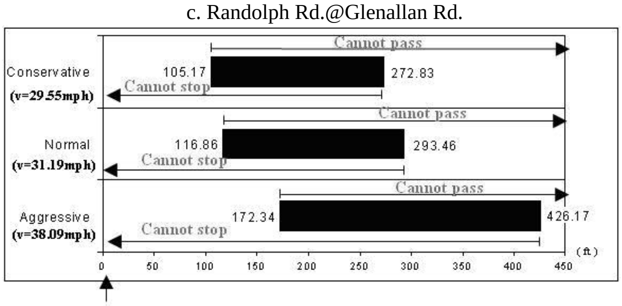
a. MD 193@MD 201



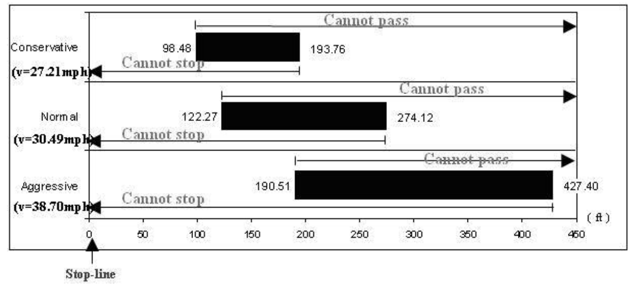
b. MD 650@Metzerott Rd.



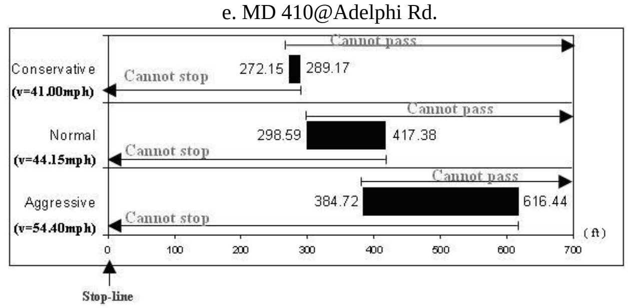
c. Randolph Rd.@Glenallan Rd.



d. MD 410@Belcrest Rd.



e. MD 410@Adelphi Rd.



f. MD 193@Mission Dr.

Fig. 8. Dilemma zones measured via the video-based system across 6 intersections in Maryland

V. CONCLUSIONS

A system based on video image processing to measure the dilemma zone distribution at signalized intersections was developed. System features and operational procedures were detailed. Field experiments conducted by using an experimental vehicle validated the effectiveness of the proposed system in measuring vehicular speed evolution profile during the yellow phase which can provide all critical data for computing the dilemma zones, such as the acceleration/deceleration rates, and the approximate reaction time to an encountered yellow phase. Using the proposed video-based system, this study has conducted extensive field observations of 1,123 drivers' responses to a yellow phase at six intersections of high accident frequency. The empirical results have clearly indicated the existence of multiple dilemma zones at all six intersections, and the location and range of those dilemma zones vary with the behavior of the driving population, which proves the capability of the proposed system in measuring and understanding the dynamic nature of dilemma zones at signalized intersections.

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