DISCUSSIONS AND CLOSURES

Discussion of "Video-Capture-Based Approach to Extract Multiple Vehicular Trajectory Data for Traffic Modeling" by Heng Wei, Chuen Feng, Eric Meyer, and Joe Lee

Alfredo García[1] and Mario Romero[2]

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The paper proposes a methodology to obtain vehicle trajectory data from videos; however, the accuracy may be improved using both of the following: another technique for coordinate conversion based on homologic transformations, and linear regression for speed and acceleration of calculation. Some comments on precision differences and sampling intervals are included in this discussion.

Coordinate Conversion

As the parameters of the mathematical projection formula for conversion are very difficult to measure in practice, a simpler method must be used, but the authors of the discussed paper propose factors to convert screen space to real space that have some imprecision. An improved technique using two consecutive homologic transformations can be adopted that turns the trapezoid on screen into a rectangle of known size. Thus, selection of reference points is simplified and calculation precision improved.

For the coordinate conversion using the homologic transformations, it is necessary to locate enough references to define four points of the street on the screen, and afterward to determine the two vanishing points of the perspective ($V1$ and $V2$). Later, from the known street dimensions (width and length), the two homologic base lines ($BL1$ and $BL2$) and the three homologic diagonals ($HD1$, $HD2$, and $HD3$) are carried out, as shown in Fig. 1.

The procedure to obtain the real coordinates of a point P in the screen space is summarized in Table 1 and Fig. 2. The real coordinate x of P will be the distance between points $P3$ and $P4$; the real coordinate y of P will be the distance between points O and $P8$.

The required number of reference points diminishes, and a more precise transformation is also obtained, without a significant increase of the algorithm complexity, since it is exclusively based on straight line equations to find intersecting points. If the street has grade changes, it is necessary to divide the street into several flat segments, applying the same procedure for each one.
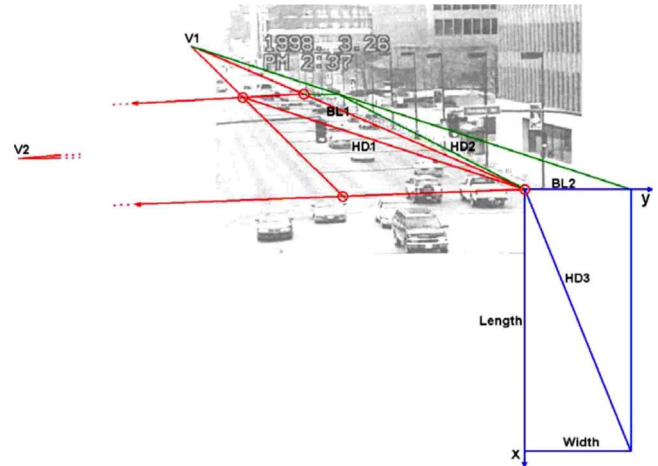

Fig. 1. Homologic transformations

Table 1. Coordinate Conversion Procedure

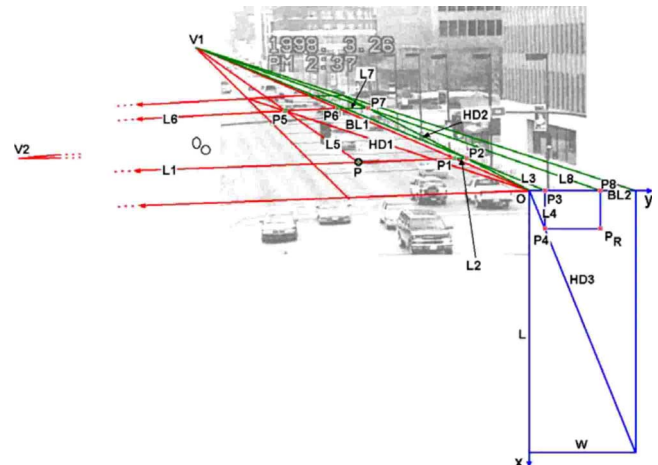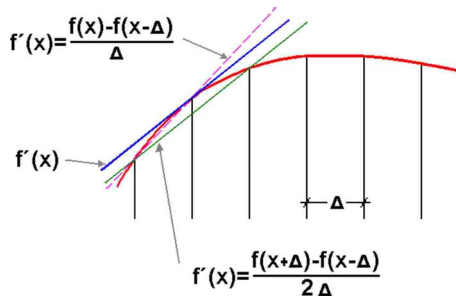| Line	From	To	Characteristic	Find intersection with	New defined point
L1	V2	P		BL1	P1
L2	P1		Parallel to BL2	HD2	P2
L3	V1	P2		BL2	P3
L4	P3		Perpendicular to BL2	HD3	P4
L5	V1	P		HD1	P5
L6	V2	P5		BL1	P6
L7	P6		Parallel to BL2	HD2	P7
L8	V1	P7		BL2	P8

Fig. 2. Coordinate conversion

Fig. 3. Derivative calculation

Calculation of Speed and Acceleration

For the speed and acceleration calculation, the following equations for the derivative calculations are suitable, from the discrete values of a function, due to the fact that, on having a long interval, it has a better approximation to the real value, as Fig. 3 shows. These equations are equivalent to calculating the slope with a three point linear regression. The speed can be obtained by the derivative of the position with respect to time [Eq. (1)]. The acceleration is defined as the time derivative of the speed [Eq. (2)]

$$f'(x) = \frac{f(x + \Delta) - f(x - \Delta)}{2\Delta} \quad (1)$$

$$f''(x) = \frac{f'(x + \Delta) - f'(x - \Delta)}{2\Delta} = \frac{f(x + 2\Delta) - 2f(x) + f(x - 2\Delta)}{4\Delta^2} \quad (2)$$

In Table 2, the variation of speed and acceleration values between Fig. 4 from the paper and those calculated using the proposed formulas can be seen. Important differences are observed in the acceleration values, with a less erratic trend and with variations of acceleration between successive points lower than 7.33 ft/s², whereas with the original values, differences of 18.42 ft/s² are observed.

Precision Differences

Since it is possible to observe these, precision differences in the calculation of the coordinates have a rate of approximately 7 to 1. Therefore, several cameras placed at different sites along the street section may be used for improving accuracy. In that case, the software should deal with various videos simultaneously.

Sampling Interval

It is important to know the frames-per-second rate of the recording system used, even with digital or analog cameras, to avoid

Table 2. Speed and Acceleration Values

No.	Time (s)	Position (ft)	Mid-position (ft)	Original speed (ft/s)	Original acceleration (ft/s²)	Proposed speed (ft/s)	Proposed acceleration (ft/s²)
Head vehicle							
0	0.00	172.73	0.00				
1	0.50	190.27	181.50	35.08		35.72	
2	1.00	208.45	199.36	36.36	2.56	33.15	−10.24
3	1.50	223.42	215.94	29.94	−12.84	25.48	−13.85
4	2.00	233.93	228.68	21.02	−17.84	19.30	−9.61
5	2.50	242.72	238.33	17.58	−6.88	15.87	−4.93
6	3.00	249.80	246.26	14.16	−6.84	14.37	−0.75
7	3.50	257.09	253.45	14.58	0.84	15.12	1.61
8	4.00	264.92	261.01	15.66	2.16	15.98	
Target vehicle							
0	0.00	112.67	0.00				
1	0.50	131.15	121.91	36.96		35.23	
2	1.00	147.90	139.53	33.50	−6.92	31.84	−5.72
3	1.50	162.99	155.45	30.18	−6.64	29.51	−0.23
4	2.00	177.41	170.20	28.84	−2.68	31.61	7.10
5	2.50	194.60	186.01	34.38	11.08	36.61	5.45
6	3.00	214.02	204.31	38.84	8.92	37.06	−0.83
7	3.50	231.66	222.84	35.28	−7.12	35.78	0.54
8	4.00	249.80	240.73	36.28	2.00	37.60	
Lead vehicle							
0	0.00	223.42	0.00				
1	0.50	246.78	235.10	46.72		44.18	
2	1.00	267.60	257.19	41.64	−10.16	40.44	−3.16
3	1.50	287.22	277.41	39.24	−4.80	41.02	0.70
4	2.00	308.62	297.92	42.80	7.12	41.14	−3.27
5	2.50	328.36	318.49	39.48	−6.64	37.75	−5.89
6	3.00	346.37	337.37	36.02	−6.92	35.25	−4.31
7	3.50	363.61	354.99	34.48	−3.08	33.44	−4.24
8	4.00	379.81	371.71	32.40	−4.16	31.01	
Lag vehicle							
0	0.00	0.40	0.00				
1	0.50	23.00	11.70	45.20		45.47	
2	1.00	45.87	34.44	45.74	1.08	46.65	2.58
3	1.50	69.65	57.76	47.56	3.64	48.05	4.00
4	2.00	93.92	81.79	48.54	1.96	50.65	2.22
5	2.50	120.30	107.11	52.76	8.44	50.27	−4.71
6	3.00	144.19	132.25	47.78	−9.96	45.94	−7.96
7	3.50	166.24	155.22	44.10	−7.36	42.31	−6.67
8	4.00	186.50	176.37	40.52	−7.16	39.27	

introducing error sources. For example, in Europe, where the PAL system is used, a 0.5-s sampling interval should not be used with the analog case, since the system records up to 25 frames per second and there would not be a whole number of pictures in the interval; therefore, it would be preferable to use an interval of 0.4 s.

Closure to "Video-Capture-Based Approach to Extract Multiple Vehicular Trajectory Data for Traffic Modeling" by Heng Wei, Chuen Feng, Eric Meyer, and Joe Lee

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[3]President, MeyerITS Insight, Inc., 3413 Aldrich St., Lawrence, KS 66045-2962. E-mail: emeyer@insighthawks.com
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Alfredo García and Mario Romero have proposed a homologic transformation method in their comments to model the algorithm for extraction of vehicle trajectory data using four reference points that are measured in the field. Theoretically, this new approach is capable of better improving the accuracy of the trajectory data. Reducing the numbers of the field reference points by this method sounds exciting. Additionally, it becomes easier to obtain the horizontal and vertical distances between the vehicle and the origin point simultaneously, i.e., X and Y, as shown in Fig. 1. However, one minor problem has been identified: $L2$ in Fig. 2 should be an extended line with $L1$ from the vanishing point $V2$ and P, rather than a parallel line to $BL2$. Similarly, line $L7$ is an extension of line $L6$ from the vanishing point $V2$ connecting $P5$ and $P6$. This is proved as follows.

If all closed shapes of Fig. 2, as shown in Garcia and Romero's description, are spread out or unfolded into a single plane, a bird's eye view' of them can be presented in Fig. 3. The screen length L' and screen width W' could be calculated in pixel rectangular coordinates, which are available in the computer system. Real field length L and width W of the roadway segment could be
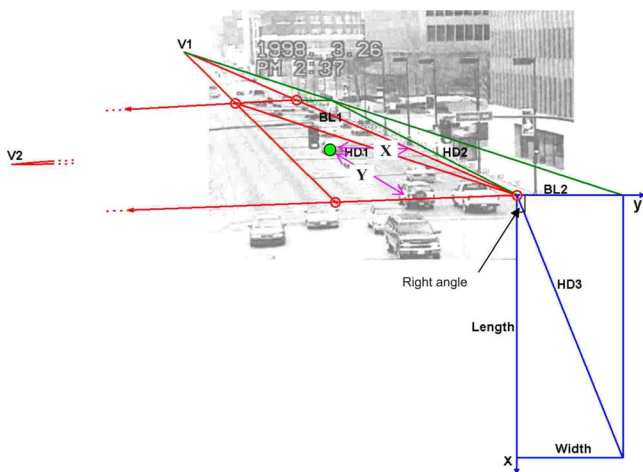

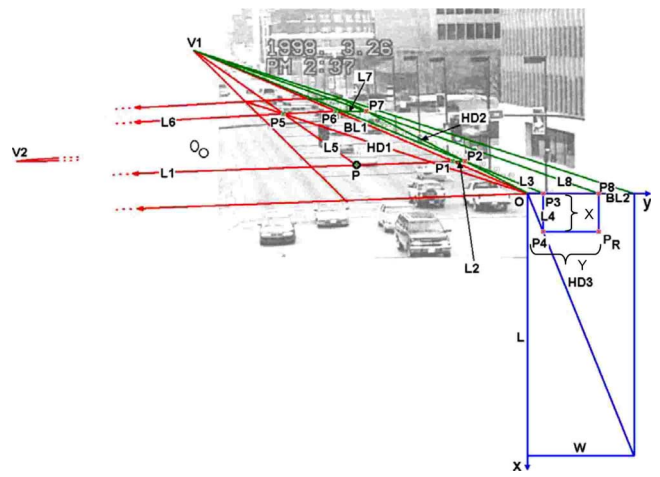**Fig. 1.** Homologic transformations based on theory of García and Romero

Fig. 2. Coordinate conversion based on theory of García and Romero

measured in the field after the four points ABCO are determined. Help lines, namely, $BL1$, $BL2$, $HD1$, $HD2$ and $HD3$, drawn as shown in Fig. 3, correspond to those lines in Figs. 1 and 2. Assuming that a vehicle is instantly positioning at P, the objective of coordinate conversion is to convert X' and Y' into X and Y given L and W, as shown in Fig. 3.

In Fig. 3, the rectangle ABOC represents the boundary of the observed roadway segment as displayed in the video. The rectangle IJFO represents the boundary of the observed roadway segment with field measures of real length L and width W. The rectangle OFGH is the "mirror" of IJFO. Obviously, rectangles IJFO and OFGH are homologic to ABOC. The rectangle BEFO has the same field width W as IJFO and the same screen length L'

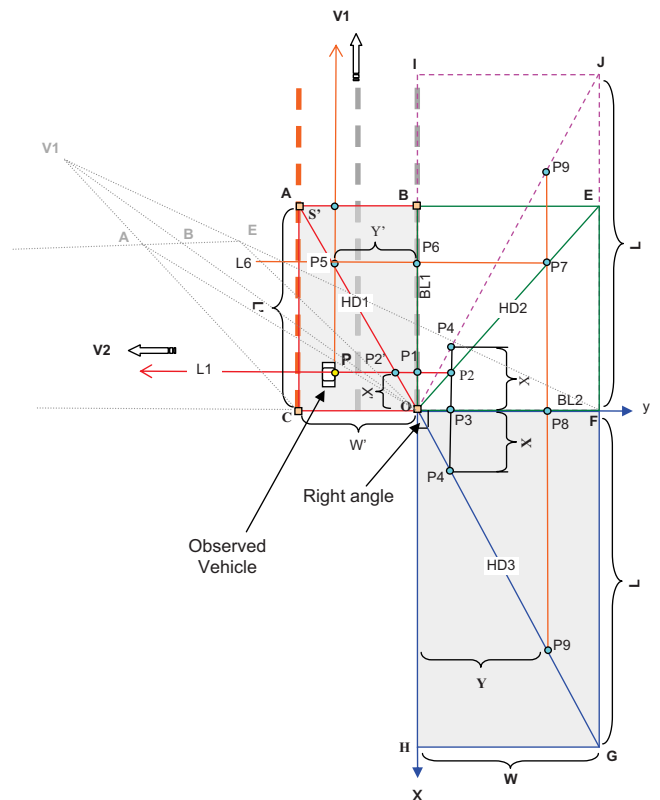**Fig. 3.** Principle of coordinate conversion using homologic transformation

Table 1. Coordinate Conversion Procedure

Line	From	To	Characteristic	Find intersection with	New defined point
L1	V2	P		BL1	P1
L2	P1		Extends L1	HD2	P2
L3	V1	P2		BL2	P3
L4	P3		Perpendicular to BL2	HD3	P4
L5	V1	P		HD1	P5
L6	V2	P5		BL1	P6
L7	P6		Extends L6	HD2	P7
L8	V1	P7		BL2	P8

as ABOC. The X' of point P is the same as point $P2'$ within ABCO. To identify the corresponding point of $P2'$ in IJFO, draw a line crossing point P parallel to $BL2$ and intersecting $HD2$ at $P2$.

Since the length of BEFO does not present the real field length, draw a line perpendicular to BL2 and make it intersects with the line OJ at $P4$. Then $P4$ is the point that presents the real field measure X of the point $P2'$, or P. To clearly display the transformation, the mirror of IJFO, i.e., OFGH, is used to reflect point $P4$ with the aid of line $HD3$, as shown in Fig. 3. The distance between $P3$ and $P4$ is X—The real distance between the observed vehicle and the origin point along the x-axis. Similarly, Y could be calculated on the same principle. In summary, the field position of P can be converted from its screen-measured position as follows:

- Given X', which is measured by the distance between O and $P1$ on screen, the field distance between O and $P1$ (i.e., X) is obtained by the distance between $P3$ and $P4$, as shown in Figs. 2 and 3.
- Given Y', which is measured by the distance between P and $P1$ on screen, the field distance between O and $P1$ (i.e., Y) is obtained by the distance between O and $P8$, as shown in Figs. 2 and 3.

Since in reality it is almost impossible to get a bird's eye view video like that in Fig. 3, the perspective effect of the video view is considered. Thus, two vanishing points, $V1$ and $V2$, exist and can be imaged as the crossing points of lines CA and OB and lines BA and OC, respectively. Line $L2$ is therefore an extension of line L1 from the vanishing point V2 connecting P and $P1$ (Fig. 2), rather than a parallel line to $BL2$. Similarly, line $L7$ is an extension of line $L6$ from the vanishing point $V2$ connecting $P5$ and $P6$. Table 1, originally proposed by Garcia and Romero, shows a summarized procedure of coordinate conversions which is then modified based on the above proofs.

After careful study of those comments and the mechanism of the homologic transformation method, the writers imbedded this method into an algorithm within VEVID and conducted tests under different geometric conditions. Although the homologic transformation method is theoretically sound, and if it is successfully employed, setting up the reference points in the field would be simplified, the testing results imply that the method has limitations, and its application should be confined to the following conditions:

- Level terrain;
- Straight and short road segment; and
- Parallel curbs or edges on both sides of the segment.

In addition, *AVI* resolution is always a contributing factor to the errors made by using the homologic transformation method, especially as the reference points are set up at farther locations. Far from the reference point, one pixel represents a longer length. The highest resolution of an AVI file is exported from a DV camcorder which we have tested is 720×480 with a frame rate of 30 frames per second. With only four reference points are set up using the homologic transformation method, it is difficult to reduce the error near two farther points, where at least a 6 ft error occurs. Unlike the method of setting up the reference points at a certain spacing (e.g., 20 ft), only four points are set in the field by the homologic transformation method, in which no other references can be used to control the error range. Therefore, it is somewhat risky to run if using the homologic transformation method. To avoid such a risk, the method with rows of reference points at 20 ft spacing was still used in the writers' recent research on dilemma zone study.

In the writers' study, 0.5 s sampling interval was used when the frame rate was set up at 2 frames per second. As a matter of fact, the frame rate of 1 to 30 frames per second could be chosen when digitizing the analog video into AVI files. This could be done easily by using a video-capture board card. For example, if the 25 frames per second were determined, the time interval between frames would be 0.04 s.

Closure to 'Video-Capture-Based Approach to Extract Multiple Vehicular Trajectory Data for Traffic Modeling,' 2009, *ASCE Journal of Transportation Engineering*, Volume 135, Issue 3, pp. 151-152 Wei*, Heng, Meyer, E., Lee, J., and Feng, C.; "Video-Capture-Based Approach to Extract Multiple Vehicular Trajectory Data for Traffic Modeling," *ASCE Journal of Transportation Engineering*, (2005) Volume 131, No. 7, pp 496-505.

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Issue 7 | July 2009 | pp. 395-489
Issue 6 | June 2009 | pp. 323-394
Issue 5 | May 2009 | pp. 253-321
Issue 4 | April 2009 | pp. 153-251
Issue 3 | March 2009 | pp. 83-152
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☐ **DISCUSSIONS AND CLOSURES** TOP

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Technical Papers

Video-Capture-Based Approach to Extract Multiple Vehicular Trajectory Data for Traffic Modeling

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Abstract: This paper presents a methodology for extracting vehicular trajectory data using a video-capture technique, and describes a computer-based tool, Vehicle Video-Capture Data Collector (*VEVID*), which was developed to help extract trajectory data from the video. The proposed methodology consists of three basic steps. First, an urban street is videotaped from an elevated position, and distances between reference points are measured and input into the *VEVID* parameters file. Second, a segment of video is digitized into a Video for Windows (*AVI*) file at a user-specified frame rate. Third, the *AVI* file is registered in *VEVID*, and then, in each frame, the user simply clicks the mouse over a distinguishable point of targeted vehicles. Trajectories are output into a trajectory data file along with speeds, accelerations, and gaps of targeted vehicles. Finally, several types of data extracted from *VEVID* that are applicable to microscopic traffic simulation modeling on urban street networks are discussed to show the capabilities of the proposed approach in traffic modeling.

Introduction

Advanced Traveler Information Systems (ATIS) and Advanced Traffic Management Systems (ATMS), two of the primary components of urban Intelligent Transportation Systems (ITS), call for an analytic evaluation which requires a correct representation of dynamic traffic flow phenomena (Mahmassani and Peeta 1995). These phenomena include lane assignment, car following, lane changing, queuing, queue discharging, and congestion buildup and dissipation. The core of a microscopic simulation model is the lane assignment model, which assigns vehicles dynamically to lanes. As the most important components of a lane assignment model, the lane choice, car following, and lane changing models have received considerable research interest. However, little research has been undertaken which examines the urban lane assignment issue, especially on the observation-based calibration and validation of traffic modes. One main reason lies in the difficulty to obtain good, simple, and clean data in a cost-effective way.

A vehicle trajectory describes the vehicle's path over a period of time. Modeling vehicle travel behaviors with interactions as well as calibration and validation of existing models, such as car-following and lane changing behaviors, relies heavily upon multiple vehicle trajectory data. Other parameters that contribute to microscopic simulation modeling, such as velocity, acceleration, and headway, can be derived from vehicle trajectory data.

In past decades, photography from an elevated position was commonly used for trajectory data collection. This generally consists of time-lapse photographs taken at speeds of 10–120 frames/min. Measuring and summarizing data from a large number of prints is very time intensive. Observations over a long period of time greatly increase the cost of analyzing and storing records. The moving-vehicle (floating-car) method is another means of obtaining trajectory data. However, it is difficult to control time measurement when the test car traverses a distance between reference points. Moreover, the moving vehicle method can deliver only one vehicle's (the test car's) trajectory during each measurement.

Because of the availability and low cost of video equipment, videotaping is becoming more and more practical to use in traffic counts (ITE 1999). Although this procedure requires more equipment than manual counts, it requires fewer personnel in the field, and videotape can be reviewed more than once, if needed. However, additional office-labor is usually required to summarize data from video manually. Using videotape, it is still difficult to accurately measure the time taken by each vehicle to traverse a number of reference points.

Thanks to the recent availability of low cost and high quality video-capture cards, and high speed, and capacity personal computers, it is now feasible to digitize full-motion video at frame rates of up to 30 frames/s.

Unlike photography, video-capture boards can capture not only still images, such as the windows bitmap format, but also full-motion images in formats such as the *Video for Windows*, or *Audio Video Interleave (AVI)* format. To help extract traffic related data from the digitized video, a computer package, called **Vehicle Video-Capture Data Collector (***VEVID***)**, was developed using *Visual Basic*. The *VEVID* extracts trajectory data from *AVI*

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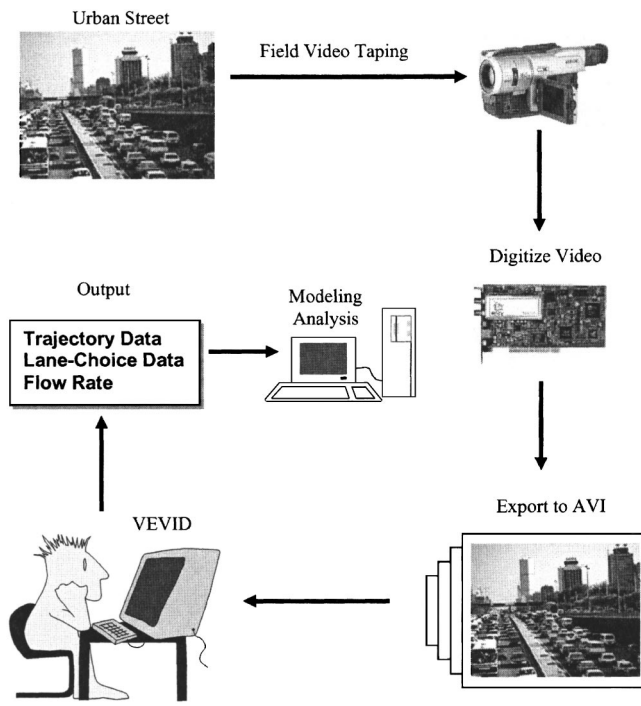
Fig. 1. Structure of data collection using video-capture technique

files that have been digitized from videotape using video-capture equipment. Much of the labor traditionally required to extract vehicle trajectory data and to calculate concerned parameters can be eliminated using *VEVID*.

This paper presents a methodology that has been developed to extract multiple vehicle trajectory data using video-capture technology in conjunction with *VEVID*. Basic concepts and approaches involved in developing *VEVID* are introduced, including some of the technical details which had to be considered, and the operation of *VEVID* is briefly described. Finally, major types of data that can be extracted from the trajectory data produced by *VEVID* are discussed. These types of data may be applicable for microscopic traffic simulation modeling on urban street networks and other traffic flow studies. The methodology proposed in this paper provides a more efficient tool for performing traffic studies.

Video-Capture Technique Used in Data Collection

Structure of Data Collection Using Video-Capture Technique

Fig. 1 shows the procedure for collecting data using a video-capture technique. This procedure consists of three basic steps. First, an urban street is videotaped from an elevated position, and distances between reference points are measured. Second, video is digitized using video-capture equipment, and a segment of video is exported to an *AVI* file at a user-specified frame rate (the default value is 2 frames/s). Third, the video must be registered in *VEVID* by developing a database of the reference points and distances between them. Then, in each frame, the user can simply click the mouse over the rear tire (or any distinguishable point) of targeted vehicles. The *VEVID* is designed to create an output data file that can be imported into common analytical tools such as *Microsoft Excel* or *Microsoft Access*.

Concepts of Video Capture

Hardware

To bring the two worlds of analog video and personal computers (PCs) together, a hardware device is needed that can capture the video and convert it to a format editable on a PC. Video-capture boards vary greatly in terms of capabilities and price, so it is important to consider the intended use of the video when choosing equipment and software. There are two properties of video capture that are particularly important for the purpose of the work discussed in this paper.
1. The capability to capture full-motion video frames from video sources at user-specified frame rates.
2. The ability to export captured video to a format that can be manipulated within a programming environment such as *Visual Basic* or *C++*. Thus, modules for traffic data extraction and analysis can be developed.

Most video-capture boards are designed to be able to create digital full-motion files, such as *AVI* files, from analog video at user-specified frame rates. A frame rate of 2 frames/s or more is generally required for collecting data to be used in microscopic traffic modeling.

Video Formats

The *AVI* is the most common format for audio/video data in the PC environment. It is a special case of the Resource Interchange File Format with uncompressed video (color format). Video-capture software provides the ability to select color formats for uncompressed *AVI* video, such as RGB15 or YUV9 (high color 16-bit in *Window 98* or higher). Only some color formats, such as YUV9 at the time of the authors' study, are editable (e.g., alphabetic and graphical objects can be added, and coordinate information can be extracted from individual frames) within a programming environment such as *Visual Basic*. With the rapid development of computer technology, however, more choice of editable color formats are expected to be available in the near future.

Video Signal Standards

Most video-capture cards have a composite video connector or an S-Video connector or both. Composite video signals are analog signals that combine luminance and chrominance (color) information in a single analog signal that can be transmitted over a single wire or stored in a single track on analog magnetic tape. An example of composite video signals is the NTSC video signals that are commonly used by commercial television sets in the United States and Japan. Composite video is particularly prone to errors in reproducing exact colors due to the overlap of the color and luminance signals. Video professionals jokingly refer to NTSC as "Never The Same Color" (McGowan 2004).

S-Video signals separate the luminance and chrominance information into two separate analog signals that can be transmitted over two separate wires or stored in two separate tracks on an analog tape. In general, S-Video is superior to composite video in reproducing colors correctly. Ordinary VHS videotape uses composite NTSC signals and the S-VHS and Hi8 video tape standards use S-Video. Thus, an S-VHS or Hi8 video camera with S-Video output to provide the analog video signal to the S-Video input of a PC video-capture card generally provides better video quality and higher resolution.

In this study, a Hi8 video camera with S-Video output was used to provide the analog video signal input for the video-capture board.

Video-Capture Using ATI Video Player

The ATI All-in-Wonder was selected as the video-capture equipment in this study. The All-in-Wonder is a two-dimensional/three-dimensional graphics board with a television tuner and integrated video-capture functions, and can digitize at frame rates of up to 30 frames/s. Two connectors on the back bracket plug into the supplied S-Video and composite input and output cables.

The vendor's capture application, the ATI Video Player, is a simple program bundled with the video-capture board that uses VCR-like controls to direct the capture and playback of video. The All-in-Wonder player can capture full-motion images in three formats: ATI Packed YUV, YUV9 Planar (Indeo Raw), and YUV12 Planar (MPEG Raw). It is noteworthy that only the YUV9 format is editable in *Visual Basic*.

Using the ATI video player, the user can capture a stream of full-motion video frames at a user-specified frame rate and save it in *AVI* format on the hard disk. The *AVI* file can be played continually by clicking the "**Play**" button. The video can be viewed frame by frame by repeatedly clicking the "**Seek**" button. The *VEVID* takes advantage of this functionality to allow users to select target vehicles for tracking.

Vehicle Video-Capture Data Collector

Features of Vehicle Video-Capture Data Collector

The *VEVID* is a personal computer software for vehicle trajectory and lane-choice data collection using a video-capture technique. The input file is an *AVI* file which is captured from the user's video source (such as a standard VCR) through video-capture equipment (such as the ATI All-in-Wonder Video Card). Since the user-selected frame rate can be used to calculate the time interval between frames, a vehicle's position change over two consecutive frames can be related to the distance that the vehicle travels during the time interval between these two frames. Based on this principle, *VEVID* was developed to extract vehicle trajectories. In addition, *VEVID* also provides the number of vehicles entering the videotaped street segment and their turning movements at both ends of the segment. The *VEVID* has several advantages over traditional traffic counting methods or equipment, including the following:

1. The capability of measuring multiple vehicles' position changes simultaneously over a time interval as small as 1/30 s, i.e., trajectory data;
2. The capability of measuring multiple vehicles' average velocities and accelerations or decelerations simultaneously over a time interval as small as 1/30 s;
3. The capability of collecting lane-choice data and all-directional lane volumes with great ease;
4. The capability to repeat counting runs to verify observations or retrieve missing data;
5. Low cost: less equipment and installations, fewer personnel and less labor required in both field and office; and
6. A short learning curve. The *VEVID* is simple to learn and use, and outputs can be saved automatically.

Coordinate Conversion

Currently available computer programming language environments such as *Visual Basic* and *Visual C++* provide the Plan Rectangular Coordinate System for describing position on a computer screen. A point location is represented by (X, Y), and the measuring unit is uniform in all directions. For example, no matter where a 10-unit-long line is placed on the screen, the 10-unit length that it represents does not change. However, this coordinate system can not be used correctly to measure any object videotaped at an angle, due to perspective related errors.

If a videotaped street is shown on computer screen with a specified size, different sections along this street with equivalent lengths measured by the Plan Rectangular Coordinate System do not represent the equivalent lengths in real-world measurement. This phenomenon is often called perspective, and is caused by the angle between the line of sight of the camera and the surface of the pavement. It is perspective that causes a roadway to appear to be narrower far away than it is nearby, when in fact, the width of the roadway is constant. In practice, the distance between a vehicle's position on two consecutive video frames can be measured directly in rectangular coordinates. Therefore, a conversion to actual length from rectangular coordinates is required before starting trajectory data collection. Otherwise, vehicle positions, velocities, and accelerations would contain unacceptable errors.

Conversion using a mathematical projection formula is commonly expressed as a function of the camera's height and line of sight angle to the targeted street. Because these parameters are very difficult to measure in practice, a simpler method was employed wherein reference points are used to define the relationship between positions and distances in the real world, called real space, and positions and distances on the computer screen, called screen space. In this method, distances measured in screen space are compared with the actual distances measured in real space. The conversion ratio along a section of the street between two immediately adjacent reference points is defined as real space divided by screen space. Table 1 shows the conversion data between reference points along Grand Avenue between 22nd and Pershing Road, Kansas City, Mo. Reference points were set every 20 ft northbound along Grand Avenue, shown by Fig. 2.

In vehicle trajectory data extraction, to keep track of a vehicle's position, the user must click the same point on the vehicle in each frame. It is recommended that the point be the point of contact between one of the tires and the pavement. Then *VEVID* can automatically calculate the point along the coordinate reference line that represents the vehicle's perspective position, called perspective point (Fig. 2). The actual distance between the perspective point and the user-defined original point at an end of street segment is the vehicle's current real-world coordinate. Speeds and other modeling-required parameters can be automatically calculated by *VEVID*, as shown by Fig. 3.

Because the choice of reference points has a significant impact on the accuracy of trajectory data, reference points should be selected carefully to reduce the perspective related errors. The *VEVID* gives clear guidance to help users input reference point locations.

Vehicle Trajectory Data for Microscopic Simulation Modeling

Microscopic simulation models focus on mimicking the lane-based movement of each individual car, various travel behaviors, traffic diversion, etc. Lane-changing, lane-choice, car-following, as well as lane-vehicle-allocation models are major components of microscopic traffic simulation system and the evaluation of ITS strategies including ATIS and ATMS (Ahmed et al. 1996). However, lane-changing and lane-choice behaviors have not been

Table 1. Coordinate Conversion Data (Grand between 22nd and Pershing, Kansas City, Mo.)

Number	X	Y	Screen space	Real space (FT)	Conversion ratio (RS/SS)
0	8,535	5,265	0	0	0
1	7,860	4,980	732.7004845	20	2.73E−02
2	7,425	4,785	1,209.338662	40	4.20E−02
3	7,050	4,620	1,619.027486	60	0.0488168
4	6,675	4,470	2,022.776557	80	4.95E−02
5	6,330	4,320	2,398.968528	100	5.32E−02
6	5,955	4,170	2,802.753111	123	5.69E−02
7	5,625	4,020	3,165.142177	143	5.52E−02
8	5,325	3,885	3,494.066399	163	6.08E−02
9	5,130	3,825	3,696.975115	177	6.86E−02
10	4,875	3,705	3,978.592716	197	7.10E−02
11	4,635	3,585	4,246.457347	217	0.0745356
12	4,545	3,540	4,346.921324	225	7.95E−02
13	4,320	3,450	4,589.166591	245	8.25E−02
14	4,125	3,345	4,809.833677	265	9.03E−02
15	4,035	3,330	4,898.390042	276	0.1205593
16	3,900	3,255	5,052.061460	296	0.1295048
17	3,660	3,150	5,314.023899	331	0.1336063
18	3,330	3,015	5,670.496010	379	0.134625
19	3,030	2,880	5,999.437474	424	0.1367882
20	2,775	2,775	6,275.165336	467	0.1559261
21	2,550	2,685	6,517.409378	508	0.1691891
22	2,340	2,580	6,751.833084	549	0.1746263
23	2,190	2,535	6,907.381921	579	0.1915653

Note: SS=screen space; RS=real space; and FT=front.

studied extensively, and most available models are based on either theoretical analyses or limited spot observations. This is mainly because of the difficulty of getting good, simple, and clean vehicle trajectory data. Additionally, most previously available models refer to lane changing behavior on freeways and do not apply to urban streets. With the development of *VEVID*, modeling lane-changing and lane-choice behaviors on urban streets have been simplified. Trajectory data are expected to examine and advance car-following modeling, as well as to calibrate predefined parameters (e.g., spacing and headway between paired vehicles, dynamic velocity, and acceleration/deceleration of targeted vehicles, dynamic lane, or link vehicle density) for simulation modeling with ease.

Basic Trajectory Data for Positioning Vehicles in Motion

Multiple vehicle trajectories provide the basis for modeling individual vehicle travel characteristics and interactions with other vehicles in traffic. Fig. 4 shows an example of the basic form of vehicle trajectory data from *VEVID*. Given the frame rate of 2 frames/s (that reflects 0.5 s between two consecutive frames),
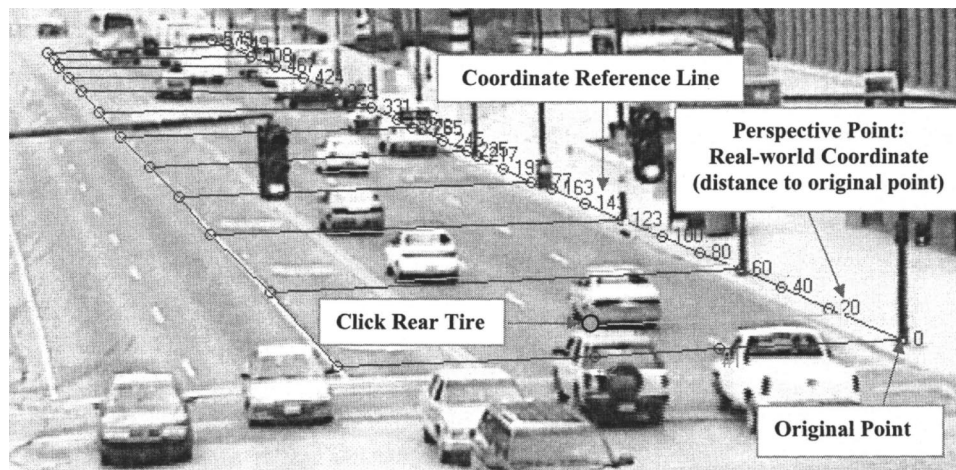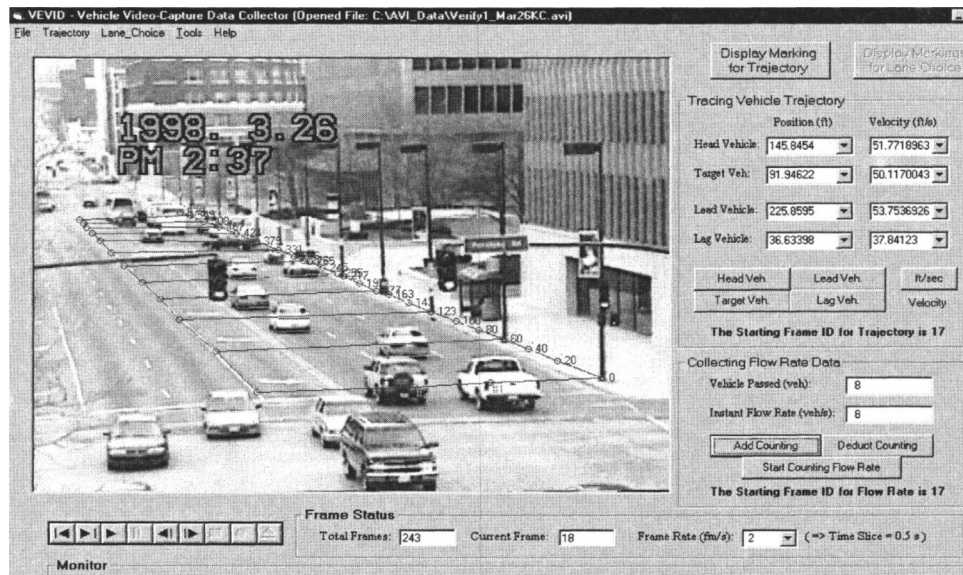

Fig. 2. Coordinate conversion

Fig. 3. Illustration of trajectory data extraction

all selected vehicles' positions are calculated by *VEVID*. Then *VEVID* automatically calculates the vehicles' speeds and accelerations for each time slice. Fig. 5 illustrates trajectory curves corresponding with the data in Fig. 4.

From Figs. 4 and 5, it can be seen that *VEVID* is not only capable of collecting trajectories of vehicles in the same lane, but also targeting multiple lanes simultaneously. This function is very valuable in the study of lane changing behaviors. Moreover, *VEVID* outputs calculation results of all traffic feature parameters that are useful to simulation modeling, such as gaps, headway, and relative speeds between each two vehicles of interest, type of lane changing, duration of lane changing, and etc.

Data for Lane-Changing Modeling

The authors' initial study (Wei 1999) suggests that a lane-changing model may be composed of a heuristic decision model, a lane-changing condition model, and a lane-changing maneuver model. In the study of lane-changing models, the lane changer is defined as the target vehicle. The car in front of the target vehicle in the same lane is defined as the head vehicle. The car in the target lane that the target vehicle intends to follow after changing lane is defined as the lead vehicle, and the car that is currently following the lead vehicle in the target lane is defined as the lag vehicle. A vehicle's lane-changing maneuver is related to interactions between the target vehicle and the head vehicle, between the target vehicle and the lead vehicle, between the target vehicle and the lag vehicle, and between the lead vehicle and the lag vehicle. Values of parameters for a lane-changing study can be directly exported by *VEVID*. Fig. 5 shows an example of trajectory curves of the head vehicle, the target vehicle, the lead vehicle, and the lag vehicle. Fig. 6 illustrates gaps between the target and the head vehicles, between the target and the lead vehicles, between the target and the lag vehicles, and between the lead and the lag vehicles, which is critical to the study of lane-changing condition models. Based on the output data in Fig. 4, all parameters can be calculated. For example, at the moment when the target vehicle makes a lane change (Fig. 5):

- The gap between the target and the head vehicle=14.7 m (48.1 ft);

- The gap between the target and the lead vehicle=40.8 m (133.8 ft);
- The gap between the target and the lag vehicle=22.7 m (74.3 ft);
- The gap between the lead and lag vehicle=63.5 m (208.1 ft);
- The velocity of the target vehicle (the lane changer) =10.5 m/s (34.4 ft/s);
- The velocity of the head vehicle=5.4 m/s (17.6 ft/s);
- The velocity of the lead vehicle=12.0 m/s (39.5 ft/s);
- The velocity of the lag vehicle=16.1 m/s (52.8 ft/s);
- The accelerations of the target vehicle (the lane changer) =3.4 m/s² (11.1 ft/s²);
- The acceleration of the head vehicle=−2.1 m/s² (−6.9 ft/s²);
- The acceleration of the lead vehicle=−2.0 m/s² (−6.7 ft/s²);
- The acceleration of the lag vehicle=2.6 m/s² (8.4 ft/s²); and
- The duration of lane changing=2.5 s.

In this way, we can determine parameter values for all observed vehicles, and then perform statistical analysis for modeling lane-changing behavior. For instance, trajectory data helped the authors quantitatively define parameters, speed advantage, and speed disadvantage, to identify one scenario of a driver's motivations during a discretionary lane-changing process (Wei et al. 2000). In the study of the speed absorption phenomenon using observed vehicle trajectory data, speed advantage is redefined as a perceptual variable for a driver to compare speed performance with the adjacent lane(s) (Tao et al. 2004). Speed advantage (SA) is described in the following mathematical equation.

$$SA = \frac{V_{LD} - V_{FT}}{V_{LD}} \tag{1}$$

where SA=speed advantage compared to an adjacent lane; 0 if $V_{LD} \leq V_{FT}$; V_{LD}=lead vehicle's speed in an adjacent lane (ft/s or mph); and V_{FT}=front vehicle's speed (ft/s or mph).

Using the SA variable, the probability of motivating a lane change incurred from a speed disturbance by the head vehicle could be estimated by the following equations, which were derived from statistical analysis of vehicle trajectory data obtained in Kansas City, Missouri (Wei 1999):

For two-way streets

```
File Name: C:\AVI_Data\Demo1_326KC.tra;
Location:Grand & Pershing, Kansas City, Missouri;
Time:2:55pm,3/26/98

Trajectory of Head Vehicle
# Time(s) Position(ft) Mid-position(ft) Velocity(ft/s) Velocity(m/h) Acceleration(ft/s^2)
0   0     172.73      86.36            ---            ---           ---
1   0.5   190.27      181.50           35.08          23.92         ---
2   1     208.45      199.36           36.35          24.78         2.52
3   1.5   223.42      215.93           29.93          20.41         -12.82
4   2     233.93      228.67           21.03          14.34         -17.80
5   2.5   242.72      238.32           17.56          11.97         -6.94
6   3     249.80      246.26           14.16          9.66          -6.78
7   3.5   257.09      253.45           14.58          9.94          0.82
8   4     264.92      261.01           15.66          10.67         2.15
9   4.5   273.07      269.00           16.29          11.11         1.27

Trajectory of Target Vehicle
# Time(s) Position(ft) Mid-position(ft) Velocity(ft/s) Velocity(m/h) Acceleration(ft/s^2)
0   0     112.67      56.33            ---            ---           ---
1   0.5   131.15      121.91           36.94          25.19         ---
2   1     147.90      139.52           33.51          22.85         -6.85
3   1.5   162.99      155.45           30.17          20.57         -6.68
4   2     177.41      170.20           28.83          19.66         -2.67
5   2.5   194.60      186.01           34.38          23.44         11.09
6   3     214.02      204.31           38.83          26.48         8.90
7   3.5   231.66      222.84           35.26          24.04         -7.14
8   4     249.80      240.73           36.28          24.73         2.02
9   4.5   269.26      259.53           38.92          26.53         5.27

Trajectory of Lead Vehicle
# Time(s) Position(ft) Mid-position(ft) Velocity(ft/s) Velocity(m/h) Acceleration(ft/s^2)
0   0     223.42      111.71           ---            ---           ---
1   0.5   246.78      235.10           46.72          31.85         ---
2   1     267.60      257.19           41.64          28.39         -10.15
3   1.5   287.22      277.41           39.24          26.76         -4.79
4   2     308.62      297.92           42.80          29.18         7.10
5   2.5   328.36      318.49           39.47          26.91         -6.65
6   3     346.37      337.37           36.02          24.56         -6.88
7   3.5   363.61      354.99           34.46          23.49         -3.12
8   4     379.81      371.71           32.41          22.09         -4.10
9   4.5   394.62      387.22           29.61          20.19         -5.58

Trajectory of Lag Vehicle
# Time(s) Position(ft) Mid-position(ft) Velocity(ft/s) Velocity(m/h) Acceleration(ft/s^2)
0   0     0.40        0                ---            ---           ---
1   0.5   23.0        11.73            45.30          30.88         ---
2   1     45.87       34.46            45.61          31.10         0.62
3   1.5   69.65       57.76            47.56          32.43         3.90
4   2     93.92       81.79            48.54          33.09         1.94
5   2.5   120.30      107.11           52.75          35.96         8.41
6   3     144.19      132.24           47.79          32.58         -9.91
7   3.5   166.24      155.22           44.09          30.06         -7.40
8   4     186.50      176.37           40.51          27.62         -7.14
9   4.5   205.51      196.00           38.02          25.92         -4.98
```

Fig. 4. Example of basic form of trajectory output from vehicle video-capture data collector

$$P(x = \text{SA}) = (0.0149 + 0.2097x + 1.1081x^2$$
$$+ 1.2074x^3 - 1.6351x^4) \times 100\% \qquad (2)$$

For one-way street

$$P(x = \text{SA}) = (0.145 + 0.1592x + 0.637x^2$$
$$+ 0.3837x^3 + 0.3197x^4) \times 100\% \qquad (3)$$

where $P_A(x=\text{SA})=$probability of generating a motivation to change to the speed-advantaged lane when $x=\text{SA}$. The correlation coefficient R^2 value for Eqs. (2) and (3) is 0.9757 and 0.9812, respectively. For example, if the front vehicle speed reduces to 13.4 m/s (30 mph) while the adjacent lane's speed remains at 22.3 m/s (50 mph), 31.1% of followers would possibly change to the adjacent lane in a two-way street. Similarly, 32.7% of followers do so in a one-way street.

Another typical application of vehicle trajectory data in simulation modeling is the calibration and validation of gap acceptance models that are used to model the execution of lane changes. Both the gap between the lead (in the adjacent lane) and the prospective lane changer (termed as "lead gap") and the gap between the prospective lane changer and the lag vehicle that is in the adjacent lane (termed as "lag gap") are major factors affecting the driver's lane-changing decisions. More significantly, these acceptable gaps are coherent with the speed of the prospective lane changer and the lag vehicle. Fig. 7 visualizes the distribution of observed lead gaps versus lane changer's speeds and lag gaps versus the lag vehicle's speeds. It presents the concerned gap and speed values at the moment as the maneuver of a lane change is started. Comparisons between the observed gap values and the recommended minimum safe gaps (minimum safety braking distances plus reacting distances at varied speeds) recommended in *Kansas driving handbook* are also presented in Fig. 7. It is obviously seen from Fig. 7 that a portion of the sampling drivers, as perform discretionary lane changes, actually accepts smaller gaps than the handbook-recommended values. Those drivers accepting no less than the handbook-recommended values are viewed as conservative drivers, otherwise as regular drivers. The critical acceptable gaps are modeled using a curve representing the lower
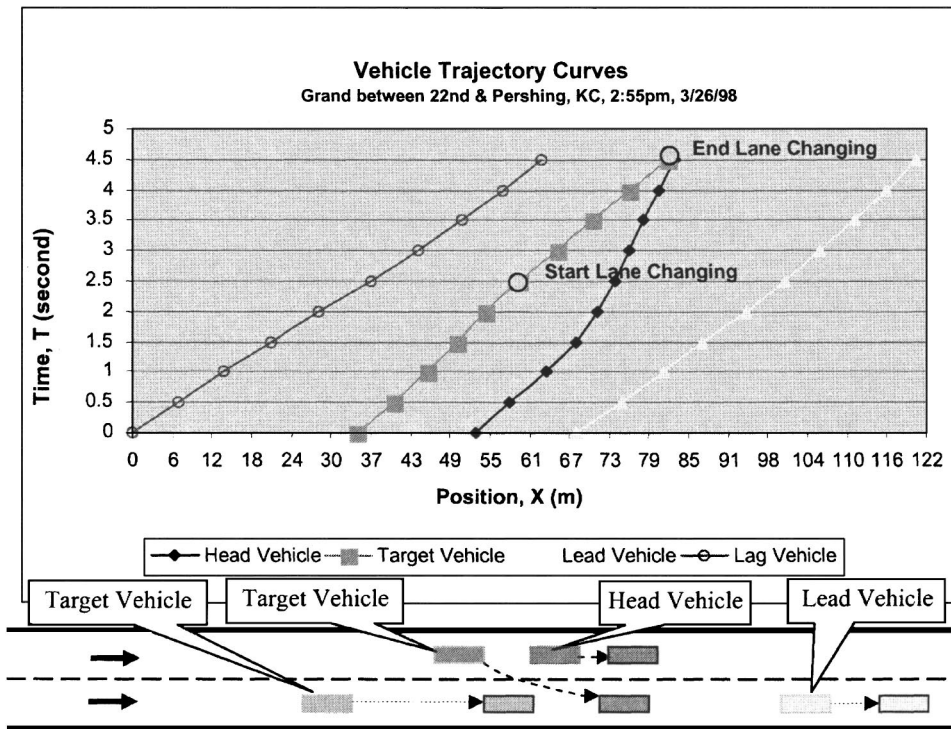
Fig. 5. Trajectory curves and lane changing illustration

boundary of the observed data, as shown by the lowest curve in Fig. 7. Acceptable gap conditions to execute a discretionary lane change can be described by the following equation after being converted with SI unit (V_{sub} is subjective vehicle's speed, m/s)

$$\text{lead/lag gap (m)} > \begin{cases} \geq 0.3336(2.2237V_{sub})^{1.6398} & \text{(conservative drivers)} \\ \geq 7.979e^{0.1244V_{sub}} \text{ and } < 0.3336(2.2237V_{sub})^{1.6398} & \text{(regular drivers)} \end{cases} \quad (4)$$

A lane changer may accelerate or decelerate when manipulating a lane-changing maneuver so as to keep a safe headway to the lead vehicle or to the lag. Acceleration varies with the individual speeds of the lane changer and the lead vehicle, as well as the differences between them. Observed maximum acceleration or deceleration values for each 4.5 m/s (10 mph) increment for determining thresholds of acceleration as simulating a lane-changing maneuver were proposed in Tao et al.'s study of car-following and lane-changing behaviors (Tao et al. 2004), which are difficult to obtain without vehicular trajectory data.

Data for Car-Following Study

Car-following models basically address speed–spacing relationships as one vehicle follows another on a straight roadway where there is no passing. Many of the car-following models proposed in the literature are single regime and do not account for various scenarios of vehicle interactions (Zhang et al. 1998). Todosiev developed Psycho-Physical Spacing models by employing perceptual psychology principles (Todosiev 1963). The important conclusions of these models are that at a large spacing, the follower is not influenced by the magnitude of the speed changes, and that at a small spacing, there are combinations of relative speed and distance headway for which there is no response from the follower. Both models suggested that a multiregime car-

following model accounts for the realistic nature of vehicle behaviors. In particular, the selection of the regime and the model is based on the speed, position, and acceleration of the target vehicle and the head vehicle.

It's commonly well known that the availability of vehicular trajectory data could lead advancement in the study of car-following behavior and modeling, especially on calibration and validation of the existing models (Tao 2003). The *VEVID* is a useful tool for collecting data needed for the study of car-
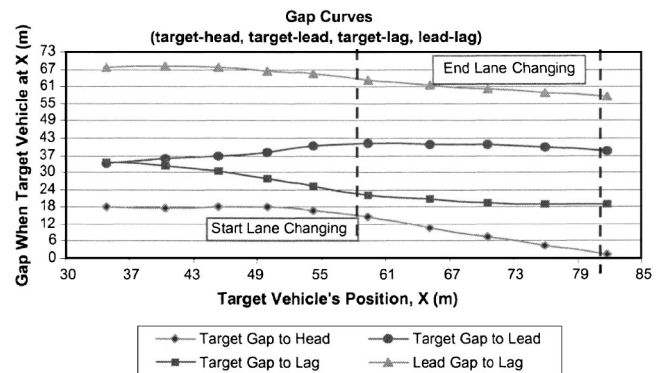

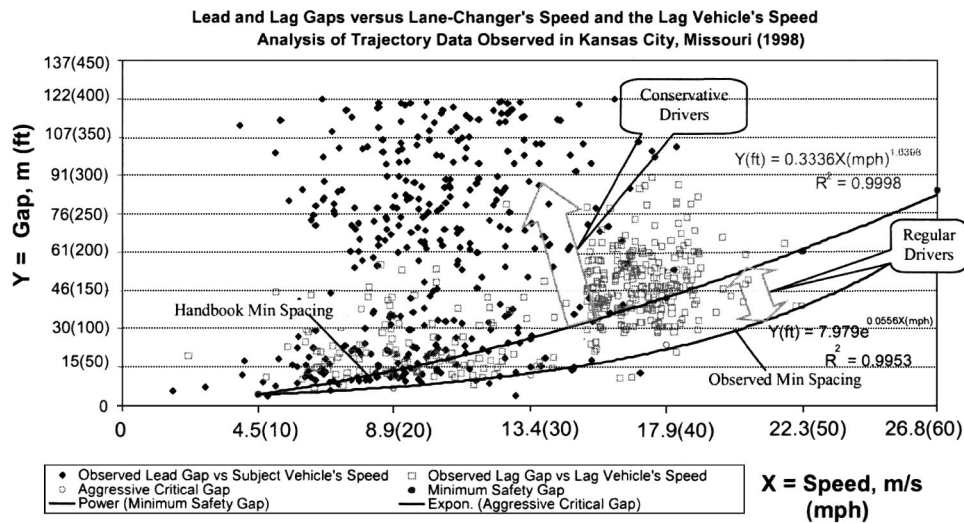**Fig. 6.** Gap curves between studied vehicles during lane change

Fig. 7. Acceptable gap conditions in adjacent lane for lane-changing decision making

following models on urban streets. For example, Tao et al. used vehicular trajectory data extracted from *VEVID* in the study of driver behaviors in a paired car-following mode in response to a speed disturbance from the head vehicle (Tao et al. 2004). As a result, they developed a concept of the State-Control Action-Expected State chains, which advances the understanding and modeling of speed disturbance phenomenon. Moreover, observed vehicle trajectory data were used to successfully identify the perceptual informative variables for lane-changing decisions and to gain applicable minimum safety spacing data in car-following and lane-changing executions.

Data for Lane-Choice Model

A lane-choice model is used to assign a vehicle to a particular lane when it is entering a street segment from an entry intersection. The term "lane choice" refers to a driver's initial lane choice when he enters an urban street segment from right- or left-turn entries. Lane choice is an important factor in accurately modeling traffic on urban streets, but it has been largely ignored in previous studies of simulation modeling parameters. Regarding lane choice, driving regulations stipulate that a driver should choose the closest lane, i.e., the rightmost lane, when he makes a right-turn entry and the leftmost lane when he makes a left-turn entry. In the real world, however, a driver may choose a nonclosest lane, because it is his target lane for an intended turning movement at the next intersection. According to the authors' study (Wei 1999), this is a frequently occurring phenomenon and has a significant impact on lane assignment.

With the use of *VEVID*, the data for calculating probabilities of various types of lane choice can be easily collected. The *VEVID* can automatically calculate values of all required parameters. Fig. 8 shows an example of output from *VEVID*, including the number of vehicles from both right- and left-turn entries, the number of lane choices, the number of vehicles with various travel directions at exit, and probabilities of all types of lane choices (see Fig. 9). As a result of analysis of observations and lane choice data, the probabilities associated with lane choice are defined in terms of the following concepts, as illustrated in Fig. 9 (Wei et al. 2002).

1. Target lane: the "best" lane chosen by a driver who intends to make a turn at the next downstream intersection when he enters the road segment from either the left-turn or the right-

turn entry. In the target lane, the vehicle can perform a turn maneuver at the exit (next intersection) without changing lanes.

2. Nontarget lane: the lane chosen by a driver who intends to make a turn at a downstream intersection when it enters the road segment from either the left-turn or the right-turn entry. In this lane, the driver has to make a mandatory lane change before he performs a turn maneuver at the exit (the next intersection).

3. Regular-choice lane: the lane, usually the closest one, chosen regularly by a driver who intends to go straight at the exit (next intersection) if he drives into the road segment from either the left-turn entry or the right-turn entry. The so-called "regular choice" means that the driver strictly follows the driving regulations.

4. Preemptive-choice lane: the lane, usually the farther one, chosen by a driver who intends to go straight at the exit (next intersection) if he makes a left-turn or right-turn entry. In other words, it is a lane in which a vehicle will make minimum number of lane changes during the remaining journey.

Conclusions

Multiple vehicle trajectories provide the basis for the microscopic modeling of traffic on an urban street network. In the past, however, the difficulty of collecting vehicle trajectory data has been an obstacle to deriving verifiable models from empirical data. This paper presents a methodology for extracting multiple vehicle trajectory data using a video-capture technique. There are two important properties of video-capture techniques that were particularly important to the development of *VEVID*: the capability of capturing full-motion video at a user-specified frame rate, and the ability to export captured video to a format that can be manipulated within a programming environment such as *Visual Basic* or *C++*. With the use of a video-capture board and *VEVID*, it becomes feasible to easily and inexpensively collect multiple vehicle trajectory data simultaneously in multiple lanes.

Introducing video capture to traffic data collection, especially multiple vehicle trajectory data for microscopic simulation modeling, is a significant advancement. The methodology proposed in

```
Output of VEVID: Lane-Choice
Time: 4:00 - 5:00 pm, 3/26/98
Location: Grand Ave between 22nd and Pershing
File name: LCD_Mar26KC_4_5pm.lcd

Vehicles From LEFT Turning Movement at Entry Intersection,
    Total No. of Vehicles from Left-Turn Entering,        148
        Total No. of Vehicles Choosing Lane #1,           74
            No. of Vehicles Turning Right at Exit Int,        24
            No. of Vehicles Going Straight at Exit Int,       50
            No. of Vehicles Turning Left at Exit Int,          0
        Total No. of Vehicles Choosing Lane #2,           74
            No. of Vehicles Turning Right at Exit Int,         1
            No. of Vehicles Going Straight at Exit Int,       72
            No. of Vehicles Turning Left at Exit Int,          1
Vehicles From RIGHT Turning Movement at Entry Intersection,
    Total No. of Vehicles from Right-Turn Entering,    70
        Total No. of Vehicles Choosing Lane #1,           60
            No. of Vehicles Turning Right at Exit Int,        34
            No. of Vehicles Going Straight at Exit Int,       26
            No. of Vehicles Turning Left at Exit Int,          0
        Total No. of Vehicles Choosing Lane #2,           10
            No. of Vehicles Turning Right at Exit Int,         0
            No. of Vehicles Going Straight at Exit Int,        9
            No. of Vehicles Turning Left at Exit Int,          1

Probability of Target Lane Choice = 0.9836
Probability of Non Target Lane Choice = 0.0163
Probability of Regular Lane Choice =  0.6242
Probability of Preemptive Lane Choice =  0.3757
```

Fig. 8. Example of lane choice observed data from vehicle video-capture data collector

this paper provides an effective and economic approach to studying microscopic traffic characteristics. With the help of *VEVID*, better quality data can be collected more efficiently. This advancement will result in better models of traffic in the urban environment. Moreover, vehicular trajectory data also have great value in calibration and validation of existing traffic models.

In addition to simulation modeling, vehicular trajectory data could be applied to other traffic analyses such as analysis of work zone merging behavior (Tao 2002). In Minderhoud's study of improved time-to-collision measures for road traffic safety assessment, vehicle trajectories collected over a specific time horizon

for a certain roadway segment are critical inputs to calculate the overall safety indicator value (Minderhoud and Bovy 2001). Trajectory data that present the tracks of vehicles traveling within the merging area of the studied work zone could provide quantitative description of merging maneuvers in terms of gap selecting, merging location selecting, speed changes, duration of merging, and so forth. As a result, impact of merging behaviors on upstream traffic could be analyzed. Trajectory data could also be used for before-and-after study of work zone traffic control strategies.

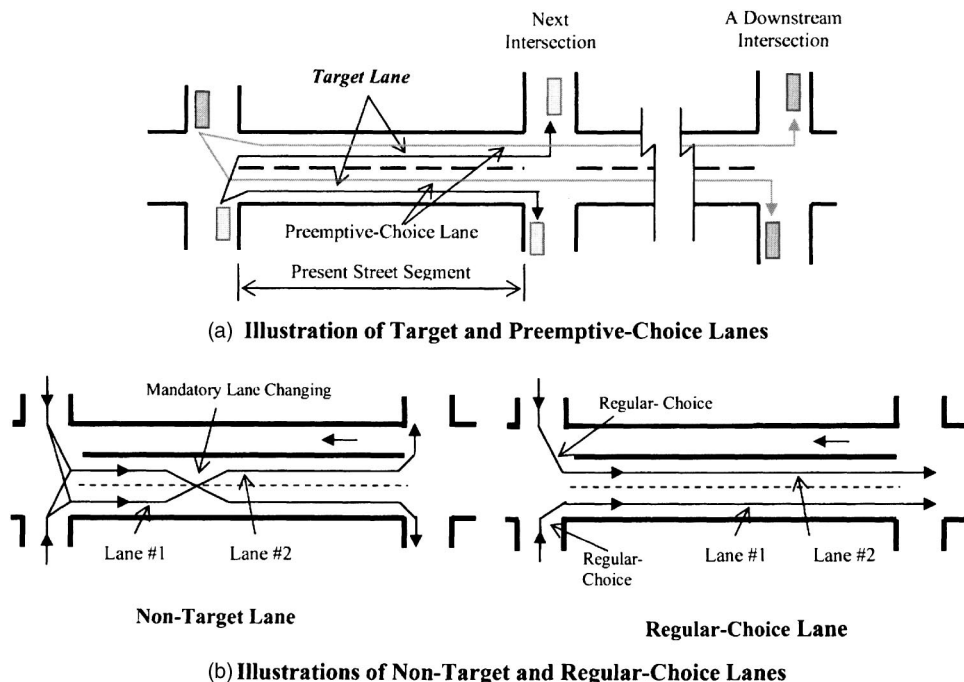The limitation of the video-capture-based approach lies in the

(a) **Illustration of Target and Preemptive-Choice Lanes**

(b) **Illustrations of Non-Target and Regular-Choice Lanes**

Fig. 9. Concepts of lane choice

extracting trajectory data of the vehicles located over 460 m or 1,500 ft away from the observation site, if a regular (family-use) camcorder is used. The far is the vehicle from the observation location, the longer distance does a pixel present in the image of an *AVI* frame. Thus, capability to produce high resolution of an *AVI* frame is one of major factors in selecting camcorder and accuracy testing is needed using sample data. In choosing place to install the camera, the site at which a very oblique camera angle is needed should be avoided if at all possible. Additionally, the model for coordination conversion at curved lanes is a new topic in future research.

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