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Performance Analysis for Design of a High-Precision Electronic Opto-Mechanical System for Vehicle Delineation Detection on Highway

We have developed a laser photodiode array based detection system that can non-intrusively detect delineations of vehicles on the highway. The U.S. Patent Office has recently approved a patent for this detection system. The system is built with low-cost off-the-shelf opto-mechanical components. The error sources from a system design point of view will be analyzed in this paper. Our study indicates that the frequency of pulsed laser diodes, computer-sampling rates, deviations in the angle of laser light and imperfectly matched detection points for sensor pairs are the main sources of error in the detection system. [DOI: 10.1115/1.1625401]

Introduction

Traffic congestion is becoming one of the most serious problems in the transportation system. The solution to this problem is to run the transportation system more intelligently, which is known as the "Intelligent Transportation System" or ITS. An Intelligent Transportation System uses intelligence to enhance the operation of the transportation system based on survey information [1–3]. Travel time is a key quantitative parameter for ITS surveillance systems [4]. In addition, travel time is a major indicator of other direct constraints on ITS efficiency: environmental emissions, fuel costs, accident risk, and driver stress. Since travel time is the parameter that the travelers most want to know, the detection of this parameter will always be of very high value.

Speed is commonly used as an indicator of the travel time across a link. Currently, the dominant technologies for detecting this parameter are magnetic loop detectors [5,6] and video monitoring systems [7,8]. The loop detector method estimates speed by inductive loops of wire that are buried beneath the road surface to count vehicles passing over them. In the video monitoring system, video cameras are mounted on poles or other tall structures looking down at the traffic scene. Video is captured, digitized, and processed by onsite computers.

An alternative methodology for traffic detection, which is the focus of this paper, involves using laser-based measurements to identify important vehicle characteristics. The initial features of this system, termed here the Laser-Based Detection System (LBDS), have been reported in [9]. Development of the system was supported by the California Department of Transportation (CalTrans). The optical and electronic designs for a field prototype have been described in [10] and a patent for this detection system has been approved recently by the U.S. patent office [11]. The laser-based system offers a number of advantages. First, the LBDS is mounted above the road and is less costly and less disruptive to install and maintain than loop detectors, which require digging up the road surface. Second, the system is insensitive to ambient lighting conditions and the primary raw data are compu-

tationally easier to process than video monitoring systems. Because video images are dependent on the lighting conditions, the measurements taken from video, even on the same vehicle, may not produce consistent results at different times of day and with different weather conditions. Furthermore, real time video image processing is problematic due to its computationally intensive nature. The LBDS uses an active lighting source (the laser). As a result, the system is independent of the lighting conditions. Also, the system operates on a simple "on/off" basis, requiring much less computation for vehicle detection.

The LBDS is a combination of several different kinds of sub-systems, including laser, optical, mechanical and electronic sub-systems. In order to obtain high precision and consistent results, this paper analyzes the error sources from components of the LBDS with a goal of finding ways to minimize errors. Using these results, the new system's precision has been improved significantly.

1 Principle of the Laser Based Detection system

Figure 1 is a conceptual drawing of the LBDS. It is composed of laser diode units and optical, mechanical and electronic components. The basic detector unit consists of a laser diode system and a photodiode array positioned above the roadway. The laser system is a pulsed infrared diode with line-generating optics that project a laser beam onto a road surface. The imaging lens focuses the reflected laser light onto the active area of a sensor array. The signal from a photodiode is amplified and sent to a computer for processing. Vehicle presence is detected based on the absence of reflected laser light. Two detector units are integrated and placed a known distance apart. Two pairs of laser/return optics are used for detecting vehicle presence at two points laterally about 4 and 8 feet across the lane. A sampling rate of about 10 kHz is generally acceptable. Any (threshold) change in the amplitude of the pavement reflectance indicates a vehicle. As shown in Fig. 1, t_1 is the time when the first laser line is blocked, t_2 is when the second laser line is blocked, t'_1 is when the first laser is unblocked, and t'_2 is when the second laser line is unblocked. We can calculate the length and the speed of a vehicle with D_{ref} , which is the distance between the two laser lines, and t_1 , t_2 , t'_1 , and t'_2 .

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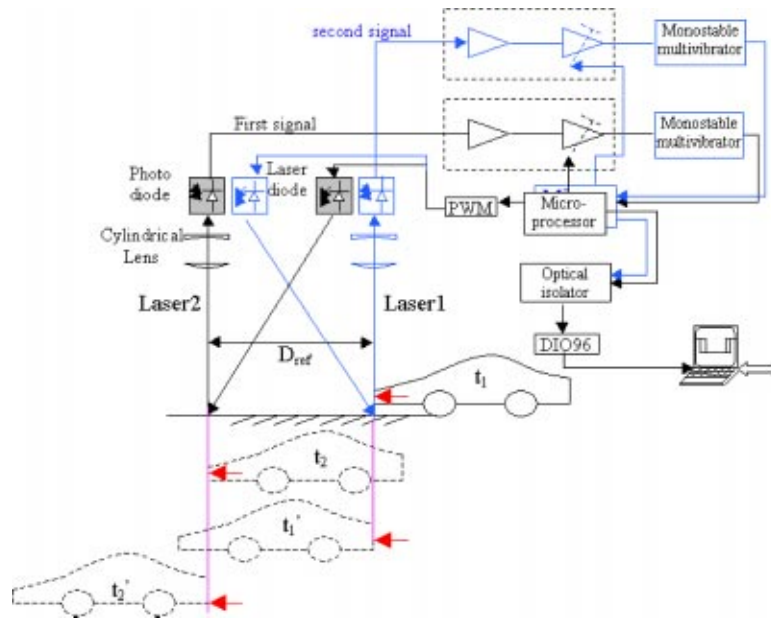
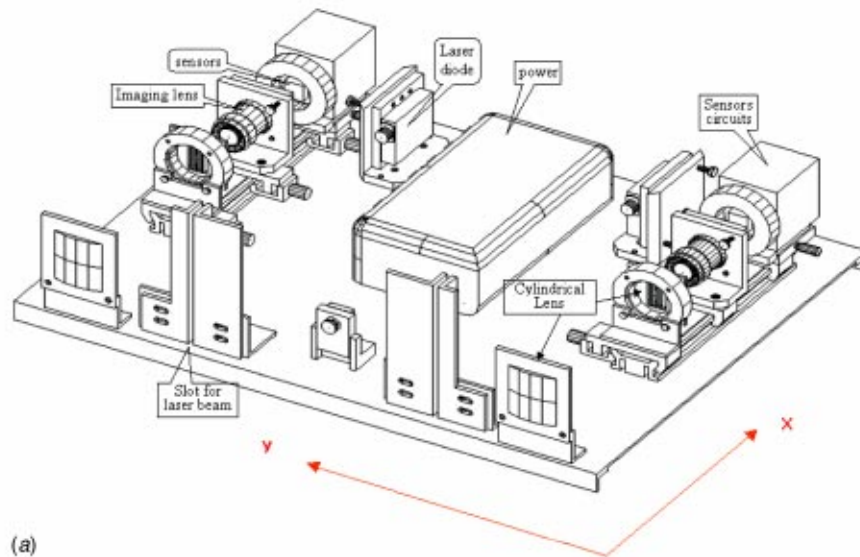


Fig. 1 Laser-based detection system schematic



(a)



(b)

Fig. 2 (a) Schematic diagram of the LBDS system; (b) LBDS prototype above the highway

1.1 Prototype of the LBDS. The LBDS system is composed of 3 subsystems: the mechanical system, the optical system and the electronic system. The mechanical system is used to adjust laser beam signals. The image of the laser is collected by the optical system and the electronic system is used to process the electronic signals. Figure 2(a) is the schematic diagram of the LBDS system. Figure 2(b) shows a prototype of the LBDS on highway. The mechanical design is flexible and allows the optical components to be adjusted to optimize alignment and focus of the reflected laser beam.

The laser is projected down to the road and reflected back to the system's sensor. The optical path is very long. Any small change in the relative position of the laser, sensor optics, or different components in the sensor optics will cause a significant shift of the image. Therefore the optical system must be adjustable after mounting.

The cylindrical lenses, imaging lenses and APD sensors are mounted on optical rails, which are mounted to the base plate. Each optical component and sensor is clamped in a mount, and is adjustable in two dimensions. The imaging lenses can be swung around an axis with the optical cell. The sensor is clamped by a ring, which is mounted to a rotating lens holder. As a result, the sensor can be adjusted via both translation and rotation.

This mechanism ensures that the linear sensor array is perpendicular to the laser line image. The lenses can swing about the X- and Y-axes shown as Fig. 2(a). The whole unit is mounted on a slide clamped to the rail. The lenses can also be adjusted in the X direction to match the axis of the telescope. After having been mounted on a bridge over highway, the optical system is easy to fit to different heights by adjusting the angle of the laser, the position of the sensor and the focus length of the imaging lens.

The electronic system includes 5 layers, as shown in Fig. 3:

1. Signal Processing: captures the laser signals, amplifies analog signals, and converts analog signals to digital signals. The laser pulse rate is about 10 kHz.
2. Device Driver: transmits signals from the circuit board to the computer. Defines how the interface operates. The sampling rate is about 10 kHz.
3. Data Reading: reads signals from the interface and stores data in RAM or onto the hard disk.
4. Computing: calculates speeds, lengths, and accelerations of vehicles from acquired data.
5. GUI: displays calculation results in a user friendly way.

1.2 Calculation of Vehicle Lengths. The length of a vehicle can be calculated based on the speed of the vehicle and the time it takes for the vehicle to pass through the detection zone. Let V_f be the front speed of the vehicle and V_r the rear speed of the vehicle. The formula for calculating the speeds (V_f and V_r) and length of a vehicle L_v can be written as shown below (assuming the vehicle acceleration, a_v , is constant):

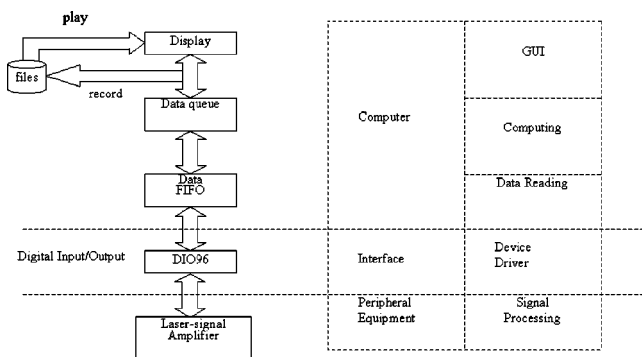


Fig. 3 System architecture

$$V_f = \frac{D_{ref}}{t_2 - t_1} \quad V_r = \frac{D_{ref}}{t'_2 - t'_1} \quad (1)$$

$$L_v = \frac{V_r + V_f}{2} \times \frac{t'_2 - t_2 + t'_1 - t_1}{2} = \frac{D_{ref}[(t'_2 - t_1)^2 - (t_2 - t'_1)^2]}{4(t_2 - t_1)(t'_2 - t'_1)} \quad (2)$$

From the above formulas, we can see that errors in t_1 , t_2 , t'_1 , t'_2 , and D_{ref} will affect the accuracy of the measurement system results.

2 Error Sources of Time Records (t_1, t_2, t'_1, t'_2)

The errors associated with measurements of time are mainly caused by the electronics, i.e., the frequency of the pulsed laser diode and the sampling rate of the computer. We discuss these error sources in the following sections.

2.1 The Effect of the Laser Pulse Frequency f_p . The frequency of the laser diode is 10 kHz in the LBDS system. The time error E_t will be caused when the vehicle arrives at the position "enter" shown as Fig. 4. Assume the vehicle arrives in the detection zone at the time T_0 . If the pulsed laser beam is dark at that time, the vehicle presence will not be detected until the time T_1 . As a result, the maximum error for E_t is:

$$E_t = +(T_1 - T_0) \approx +1/f_p \quad (3)$$

Since the pulse-to-period ratio is 15/100 000, the time difference $T_1 - T_0$ can be considered to be the period of the pulse. This error is considered positive, because the actual time is larger than the detected time. The same error will be generated when the vehicle leaves the detection zone at the position "leave." But this error is negative since the actual time is smaller than detected time. So the maximum of total error caused by the frequency of the pulse is:

$$E_p = E_t \approx 1/f_p \quad (4)$$

Assume the speed of a vehicle on the highway is V and the length of the vehicle is L . The time τ that it takes a vehicle to pass through the detection zone is $\tau = L/V$. We will define the error-time ratio $\xi_1 = E_p/t = V/(Lf_p)$. If we use the characteristic values $V = 70.0(\text{MPH}) * 1609(\text{meters/mile}) / (60 * 60(\text{seconds/hour})) \text{ m/s}$ and $L \in [3, 25](\text{m})$, then it is found that $\xi_1 \in [1.04 * 10^{-3}, 1.25 * 10^{-4}]$. These results also indicate that higher frequencies lead to smaller errors.

2.2 The Effect of the Sampling Rate f_s . The input signal of the digital input-output board (DIO96) is shown in Fig. 5. The computer will sample the signal at the frequency f_s . Similarly, the time error for sampling E_s is:

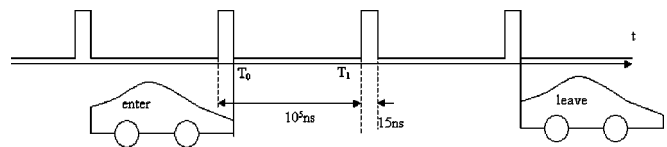


Fig. 4 The position of the vehicle

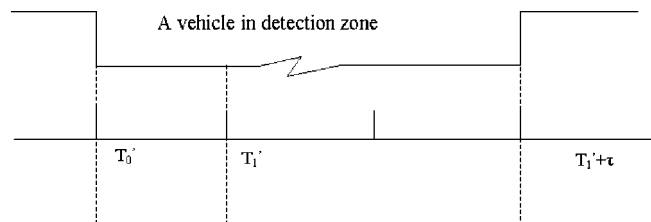


Fig. 5 The signal wave versus sampling wave

$$E_s = (T'_1 - T'_0)_t = 1/f_s$$

The frequency of vehicle signals can be estimated based on the following assumptions: the shortest length of a vehicle is 3 meters and the following distance is sufficient that times between vehicles are at least 3 seconds [12]. As a result, the highest signal frequency (f_v) for vehicle signal detection on the highway is as follows.

$$f_v = \frac{1}{\tau+3} = \frac{1}{2.2374 \frac{L}{V} + 3} = \frac{V}{2.2374L + 3V}. \quad (5)$$

where $(1 \text{ MPH}) = (1 \text{ miles per hour}) = (1609/60 \cdot 60) \text{ (m/s)} = (2.2374)^{-1} \text{ (m/s)}$.

The maximum value for f_v is 0.333. According to Shannon's Sampling Theorem, the sampling frequency f_s (about 10 kHz) used in the LBDS system is fast enough ($f_s \gg 2f_v$). Because $f_s = f_p$, the error is the same as the error caused by the pulse. The error-time ratio caused by the sampling rate is $\xi_2 = \xi_1$.

3 Error Sources Related to the Distance Between Two Laser Lines

The reference distance D_{ref} between two laser lines is another important parameter for calculating speed and length of vehicle. The value of D_{ref} is used in the software. However, this value may be changed by adjustment of the opto-mechanical subsystem and the distance between the LBDS system and the detected objects. Relevant error sources are discussed below.

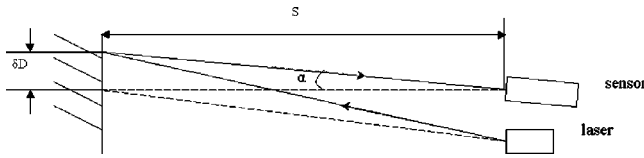


Fig. 6 Deviation Angle

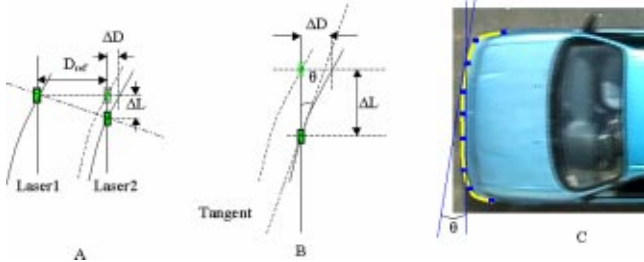


Fig. 7 Sensor positions

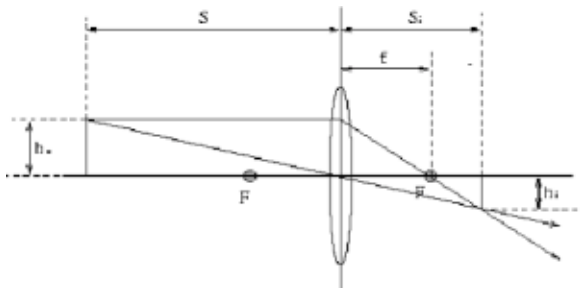


Fig. 8 Imaging of laser

3.1 The Effect of the Deviation Angle alpha of Laser Beam.

Ideally, the reflected laser light path should be perpendicular to the roadway as shown in the dashed line in Fig. 6. In reality, however, machining error or assembly error will cause a deviation angle α . The distance D_{ref} indicated in Figure. 1 will be changed to $D_{ref} \pm 2\delta D$ where $\delta D = S \tan \alpha$.

The error-distance ratio ζ_1 is:

$$\zeta_1 = \frac{2\delta D}{D_{ref} \pm 2\delta D} = \frac{2S \tan \alpha}{D_{ref} \pm 2S \tan \alpha}. \quad (6)$$

In the LBDS, the angle α is related to the tolerance of machining and assembling.

3.2 The Effect of Unmatched Sensor Detection Points.

The detection points of one pair of sensors should be ideally at the position shown as the horizontal dashed line in Fig. 7(a) (this line is perpendicular to laser lines). But in reality, it is possible that the detection points of one sensor pair are located at the position illustrated by the dotted-dashed line in Fig. 7(a). In this case, if the front or rear of the vehicle is straight, the distance (D) between two laser beams is still D_{ref} . If the front or rear border of the vehicle is curved, D will be changed to $D_{ref} \pm \Delta D$. We can develop a relationship for ΔD as shown below.

$$\Delta D = \Delta L \tan \theta. \quad (7)$$

Here, θ is the angle between the tangent line and the laser line shown in Fig. 7(b). For illustration, Figure 7(c) shows the front of a vehicle.

The purpose of the receiving lens system is to image the large laser line onto the smaller active area of the photodiode array. Suppose ΔL is the detection point deviation of one pair of sensors. The corresponding image Δl will be very small. Consider also that the focal length of the telescope is f and the distance to the object is S , as shown in Fig. 8. According to imaging principles, we can obtain [13]:

$$\frac{\Delta l}{\Delta L} = \frac{f}{S-f}, \quad (8)$$

$$\Delta D = \frac{S-f}{f} \Delta l \tan \theta. \quad (9)$$

Generally, S is about 7–9 m, and f is only 16 mm. As a result, very small Δl values will cause large ΔL values, i.e., $(\Delta l)/(\Delta L) \ll 1$.

For $f \ll S$, ΔD can be approximated as:

$$\Delta D = \frac{S \Delta l \tan \theta}{f}. \quad (10)$$

As a result, the error-distance ration ζ_2 is:

$$\zeta_2 = \frac{\Delta D}{D_{ref} \pm \Delta D} = \frac{S \Delta l \tan \theta}{f D_{ref} \pm S \Delta l \tan \theta}. \quad (11)$$

4 Total Error Analysis

Considering all of the above factors, the outputs of the system (speed and length) are illustrated below.

4.1 The Speed Error. The actual speed (V_{real}) of the vehicle is

$$V_{real} = \frac{D_{ref} \pm 2S \tan \alpha \pm \frac{S \Delta l \tan \theta}{f}}{T_{ref} \pm \frac{1}{f_p} \pm \frac{1}{f_s}}$$

$$= \frac{D_{ref} \pm 2S \tan \alpha \pm \Delta l \tan \theta / f}{D_{ref} \pm \frac{2V_{ref}}{2.2374f_p}} V_{ref}(\text{MPH}) \quad (f_p = f_s).$$
(12)

Where $V_{ref} = D_{ref} / T_{ref}$ (here T_{ref} means the detected time difference: $(t_2 - t_1)$).

The effects of varied factors on the speed are shown in Fig. 9 as

below, where the speed relative error is defined as $(V_{real} - V_{ref}) / V_{real}$, and D_{ref} as 0.5 m.

4.2 The Length Error. Assume that the detected length of a vehicle is L_{ref} , the real length of the vehicle is L_R , the average of speed of the vehicle is $\bar{V}_{real} = (V_{real1} + V_{real2}) / 2$, and the average time that a vehicle passed through underneath the detecting system is \bar{T} . According to the results for D_{ref} and T_{ref} , we can obtain the following equations (where V_{ref1} is the front V_{ref} , V_{ref2} is the rear V_{ref} and $V_{ref} = D_{ref} / (t_2 - t_1)$):

$$L_R = \bar{V}_{real} \times \bar{T}_{real}, \quad (13)$$

$$\bar{T}_{real} = \bar{T}_{ref} \pm 2/f_p = L_{ref} / ((V_{ref1} + V_{ref2}) / 2) \pm 2/f_p, \quad (14)$$

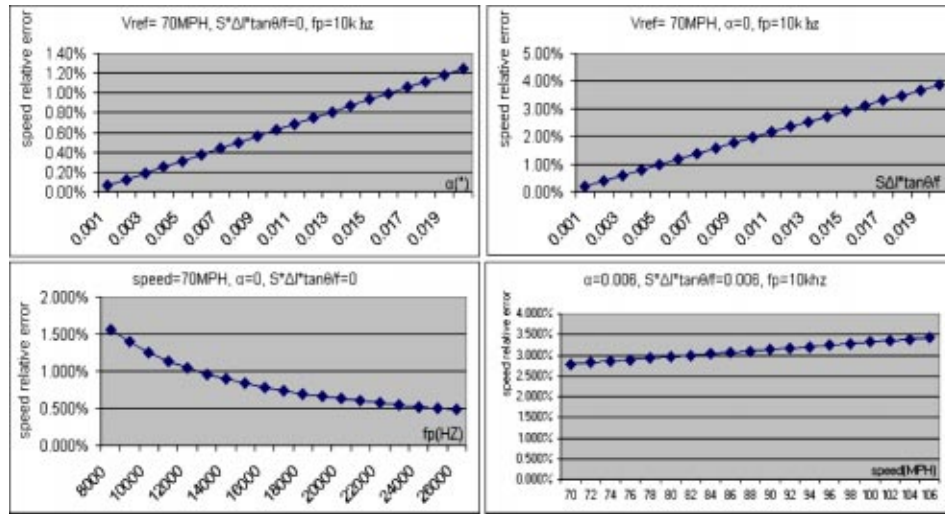


Fig. 9 Speed relative errors

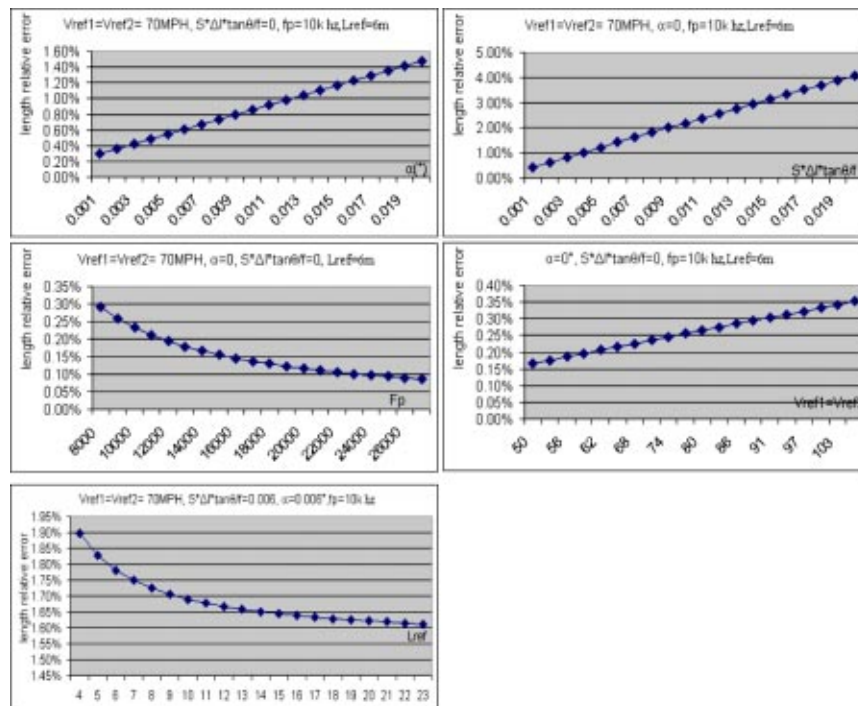


Fig. 10 Length relative errors

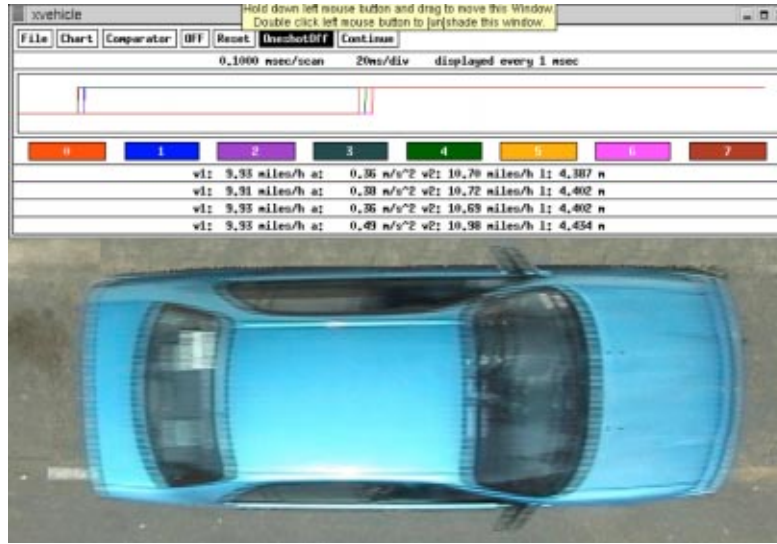


Fig. 11 Test result

$$L_R = \left(\frac{(D_{ref} \pm \varepsilon_1 \pm \varepsilon_2) V_{ref1}}{D_{ref} \pm 2V_{ref1} / 2.2374 f_p} + \frac{(D_{ref} \pm \varepsilon_1 \pm \varepsilon_2) V_{ref2}}{D_{ref} \pm 2V_{ref2} / 2.2374 f_p} \right) \times \left(\frac{L_{ref}}{V_{ref1} + V_{ref2}} \pm \frac{1}{f_p} \right), \quad (15)$$

where:

$$\varepsilon_1 = 2S \tan \alpha$$

$$\varepsilon_2 = S \Delta l \tan \theta / f$$

The length errors caused by α , $S \Delta l \tan \theta / f$, f_p , speed and L_{ref} are shown in Fig. 10, where the length relative error is defined as $(L_R - L_{ref}) / L_R$.

5 Improvement of the System

The analyses in this paper have served as a guide for improvement of the LBDS system. Based on these analyses we should make every effort to minimize the $2 * S * \tan \alpha$ and $S * \Delta l * \tan \theta$ terms and increase the frequency of the pulsed laser diodes and the computer sampling rate. Since S is constant and θ depends on vehicles, the adjustable variables are only α , Δl , and f_p . The parameter α can be adjusted as follows: we adjust the laser diode and optics so as to have almost the same distance between two laser beams at the condition of different S to minimize α . A rotatable stage is designed for the laser source. The variable Δl also can be adjusted to minimum values by adjusting the positions of sensors and optics. Two degrees of freedom are added into the stage holding the sensors. One is in the direction parallel to the laser beam line. The other is in the direction perpendicular to the laser beam line. The telescope is mounted in a stage with two rotary degrees of freedom. It was adjusted to keep the sensor arrays parallel to the laser beam line. From Fig. 9, if we adjust α and Δl to be as small as possible, for instance 0.001 deg and 1 mm, they will have very small effects on speed measurements. The main factors affecting the measurement uncertainty are the frequency of the pulsed laser diode and the sampling rate of the computer. The frequency of the pulsed laser is limited by ANSI for the safe use of lasers [14], in which the Maximum Permissible Exposure for small-source ocular exposure to a laser beam is defined. In our calculation, a laser frequency of less than 10 KHz with 60 W peak power and 10 ns duration pulsed laser is eye safe [15]. At higher pulse rates (and with the same peak power and pulse duration) the laser may not be eye safe. If the real time

operating system of computer is fast enough to sample the signal, the fastest sampling rate should be used to achieve the highest precision of the system.

From Figs. 9 and 10 ($D_{ref} = 0.5$ m), we can find that the length relative errors are very similar to the speed relative error. Since the ranges of α and Δl are very small, they have less impact on system precision. The frequency of the pulse laser diode and the sampling rate will mainly cause the system errors. An uncontrolled factor of the LBDS is the curvature of the vehicle. But if we can ensure that the detection points of sensors on two sides are on the same level, the curvature will not generate any effect on our results.

6 Test Results

Test results obtained at a UC Davis test site are shown in Fig. 11. A digital video camera was used to record the vehicle passing through the detection system. The front speed ($v1$), rear speed ($v2$), acceleration (a), and length (l) of the vehicle are displayed on the upper part of the window. Each line corresponds to one pair of sensor elements. Currently we only display four pairs of sensor elements. The results in Fig. 11 show that the signals for the new field prototype system are clear and that the transition is fast enough for measurement. The system is consistent in measuring vehicle lengths and speeds in that the speeds of the four channels are very close. The front speed is about 4.44 m/s (9.93 mph), and rear speeds are about 4.78 m/s (10.7 mph). The average length of the vehicle is about 4.4 meters. In this case, according to the calculation of Eq. (15) above, the relative length error is about 0.31% at $\alpha = 0.001$, $S \Delta l \tan \theta = 0.001$. If $\alpha = 0$, $S \Delta l \tan \theta = 0$, then the relative length error will be 0.05%. The vehicle lengths, which vary because of bumper curvature, differ from the actual vehicle lengths by only about 0.14%. These results are smaller than the maximum calculated errors. In addition, these errors are smaller than for our previous version of the LBDS apparatus.

7 Conclusions

This paper has provided analyses of potential error sources in the LBDS apparatus. The analyses presented here have served as a guide for improvement of the LBDS apparatus to its current status. Test results at UC Davis show that the length errors in the present version of the system are about 0.14% or less. These errors are lower than the maximum errors estimated in this paper. In addition, these errors are lower than for our previous versions of the LBDS apparatus.

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