Development and Field Test of a Laser-Based Nonintrusive Detection System for Identification of Vehicles on the Highway

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***Abstract*—A real-time laser-based nonintrusive detection system has been developed for the measurement of true travel time of vehicles on the highway. The detection system uses a laser line that is projected onto the ground as a probe. The reflected light is collected and focused into a photodiode array by an optical system. Vehicle presence is detected based on the absence of reflected laser light. By placing two identical laser/sensor pairs at a known distance apart, the speeds of both the front and rear of a vehicle are measured based on the times when each sensor is triggered. The length of each vehicle is determined by using these speed measurements and the residence time of the vehicle under each sensor. Using real-time software, the speed, acceleration, and length of a detected vehicle can be calculated and displayed simultaneously. A new prototype system has been tested on the highway with different types of vehicles and scenarios, and the results are presented here. The tests have also been carried out for different weather conditions and road materials. The results indicate that the laser system operates well under real highway conditions.**

***Index Terms*—Intelligent transportation systems, laser-based detection system, real-time vehicle detection.**

I. Introduction

BOTH the California Department of Transportation (Caltrans) and the U.S. Department of Transportation have come to the conclusion that it is impossible to build our way out of traffic congestion. The solution is to run the transportation system more intelligently, which is known as "Intelligent Transportation System" (ITS). Travel time is known as the most important aspect of the ITS, because travel time is a good indicator of other direct constraints on ITS efficiency: cost, risk, and attentive workload [1], [2]. The importance of travel time is verified in advanced traveler information system user surveys, which indicate that what travelers almost always want from a transportation system are reduced travel time and higher reliability (e.g., reduced travel time variance and reduced risk) [1], [2]. Every traveler must implicitly or explicitly make an assessment of these various travel time options before embarking on every trip; therefore, this information is definitely of high value. Because trip travel time is the parameter the public most wants to minimize, this is the parameter that is most important for transportation service providers to measure and minimize.

Speed is commonly used as an indicator of the travel time across a link. In current practice, speed is measured at one or more points along a link and extrapolated across the rest of the link [1], [2]. This extrapolation method is used regardless of the mechanism of detection. Example detection methods are loops [3], which determine speed from two elements 20 ft apart, video image processing, which tracks vehicles across the pixel elements within the field of view of a camera [4] or radar, which can directly determine speed from the carrier frequency shift (Doppler effect). Inductive loops and video image processing are the most commonly used methods to capture link travel time. However, both systems have certain disadvantages and limitations in practical use. For loop detection systems, installation and maintenance requires heavy equipment, and traffic must be rerouted because loops are buried beneath the pavement [5]. Furthermore, loop detectors cannot be relied upon to produce accurate speed (and therefore length) measurements because the inductive properties of the loops and the loop detectors vary. Video can be used to directly measure the length of vehicles; however, the use of real-time video image processing is problematic due to its computationally intensive nature. Also, since video is a passive system (gathering ambient light), video images are dependent on the lighting conditions. Vehicle length measurements taken from video, even on the same vehicle, may not produce consistent results, depending on time of day and weather conditions. For truly site- and time-independent vehicle length measurements, video would require an external source of illumination.

Manuscript received June 23, 2001; revised September 16, 2004. This work was supported with funding from the California Department of Transportation through the PATH program at the University of California–Berkeley. The Associate Editor for this paper was H. Dia.

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Digital Object Identifier 10.1109/TITS.2005.848364

An alternate method to determine the traverse travel time (e.g., the true link speed) is to use vehicles as probes (VAP). A VAP system determines travel time directly by identifying vehicles at the start of the link and reidentifying them at the end of the link, with the time difference being the true travel time. The problem with VAP systems is that they require large numbers of both vehicle tags and tag readers, and the cost justification of such a system seems unwarranted in the light of other options. The key aspect to measuring the actual travel time is simply to identify some distinguishing characteristics on a vehicle at the beginning of a link and then to reidentify that same characteristic on the same vehicle at the end of the link. This is the basic idea of VAP; however, the characteristic does not have to be entirely unique (as in a vehicle tag), and it does not necessitate the infrastructure set-up costs of VAP. If a characteristic can be found to separate the fleet into (say) 100 classifications, "the maximum probability fit" can be determined for the same sequence of classifications at the downstream detector as was identified at the upstream detector. This is what is currently being done in Germany with the low-resolution imaging provided by (new high-speed) loops [1], [2], [6]. If a higher-resolution detector is used so that it is possible to get a few thousand classes, then it should be quite possible to perform a 100% upstream–downstream origin and output (O/D) analysis (even if a significant percentage of the vehicles switch lanes) using time gating and other relatively straightforward signal-processing techniques. The mechanism of detection must allow highly resolved delineations between commonly available "commuter" vehicles, because commuter vehicles represent the majority of the vehicle stream during the period that traverse travel time information is most needed (e.g., the peak hours).

A laser-based nonintrusive detection system has been developed in the Integration Engineering Laboratory at the University of California–Davis (UC Davis) for the measurement of delineations of moving vehicles. The data on vehicle delineations can be used to identify and reidentify vehicles and to determine true travel time. Our laser-based detection system has a number of advantages over other systems currently in use. Advantages of our system over loop detectors are the relative ease of installation and maintenance and relatively high resolution. Our system is mounted above the road and once installed, it can be maintained without disrupting the flow of traffic. Compared with video image-processing method, our system operates on a simple "ON/OFF" basis, requiring much less computation for vehicle detection and, consequently, much less computational hardware. Also, because our system is active (using a laser for illumination), the test results are independent on the lighting conditions.

One system that bears some similarity to the system we have developed is the automatic vehicle dimension measurement system (AVDMS) developed by the University of Victoria [7]. The AVDMS uses laser time-of-flight data to classify vehicles based on length, width, or height; it is based on the Schwartz Electro-Optics Autosense III sensor [8]–[11]. The Schwartz systems are entirely dependent on time-of-flight laser measurements with moving parts, similar to conventional lidar (laser radar) in the principle of measurement. There are some significant functional differences between our system and Schwartz's. For example, the fundamental mechanism of detection is that the Schwartz detector determines the range (or distance) from the detector to the objects being detected. Our detector functionally does not determine the range (or distance) from the detector to the objects being detected. The laser of the Schwartz detector reflects off the vehicle to determine the size, shape, and "presence" of the vehicle. In our detector, the laser reflects off the pavement. The lack of a reflection determines the size, shape, and presence of the vehicle. Our system will be more reliable because of its simplicity.

An earlier system, which was developed to verify the principle of the measurement, is described in [12]–[14]. A new field prototype system has been built for field testing [15]. The present paper presents a brief description of the system and recent test results obtained on the highway with real traffic and in different weather conditions. Results from experiments at UC Davis under various environmental conditions are also presented.

II. System Overview of the Field Prototype

The system operates in the following manner, as illustrated in Fig. 1. The detector consists of two laser/sensor pairs. Each pair has a laser module and a spatially offset sensor. The detector is positioned above the plane of detection (the road surface). The laser inside the laser module is a pulsed infrared laser diode. The laser module utilizes line-generating optics to generate a laser beam and to project it to the road surface where objects are detected. The sensor consists of sensor optics, a linear photodiode array, and sensor electronics. The photodiode array sits between the sensor optics and sensor electronics. The offset sensor receives the reflected laser light emitted from its laser module counterpart. The signal outputs of the photodiode array are amplified by the sensor electronic circuits and sent to a computer for processing. Vehicle presence is detected based on the absence of reflected laser light. Two laser/sensor pairs are integrated and placed a known distance apart, allowing the velocity of the object and its residence time under the detector to be measured, giving the object's length and top-down outline profile.

The detection is based on the "critical height" principle. The critical height is the minimum vehicle height that can completely block the reflected laser while the vehicle is under the sensor. The detector is mounted at a distance of about 6.4 m (21 ft), the height of a typical highway overpass, above the highway. The distance between each component of a laser/sensor pair is 30.5 cm (1.00 ft). The offset between the two sensor pairs is 10 cm (4 in). The sensors are mounted in a fixed vertical position, pointing downward, and are focused on the ground, forming two detection zones. The lasers are pointed toward the detection zones and are mounted at an adjustable angle, allowing the system to be mounted at different heights. The detection zones stretch across the width of the lane and are each

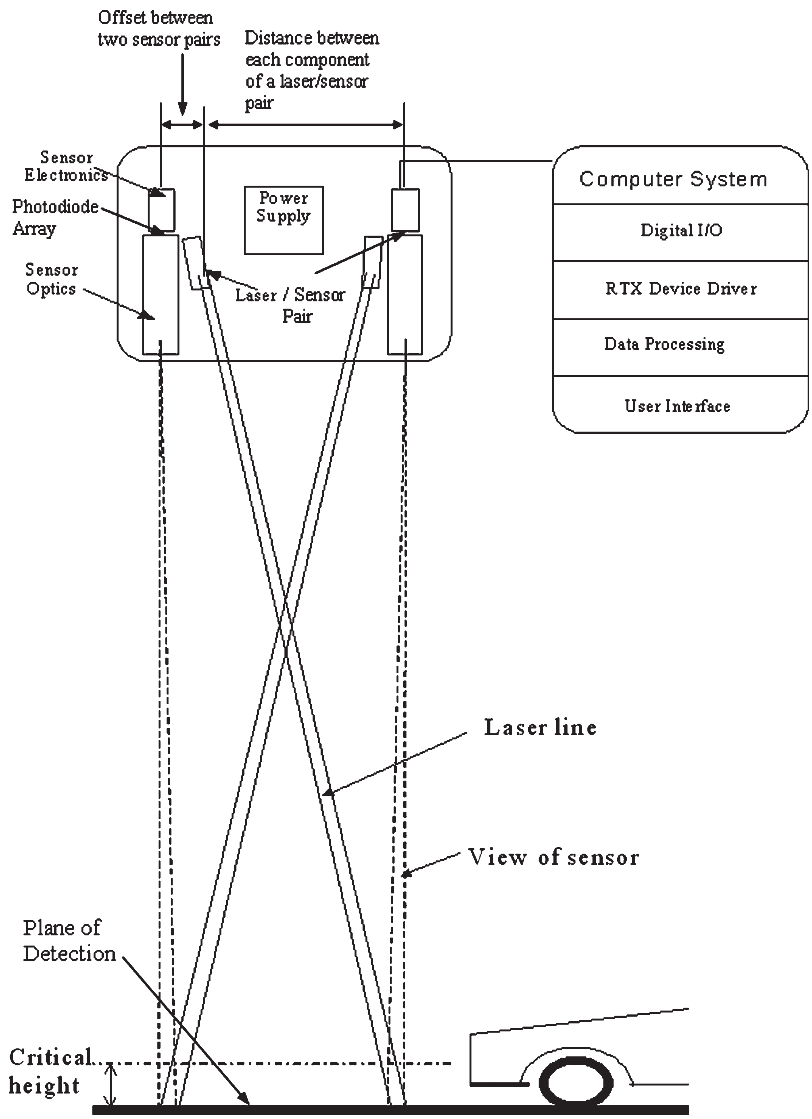

Fig. 1. System overview.

about 13 mm (0.5 in) wide in the direction of traffic flow. In this configuration, the critical height is about 46 cm (18 in). This is lower than the bumper heights of most common vehicles. For objects below this height, the laser line will still be visible by the sensor if the laser reflects off the objects. This can result in the object remaining undetected or can cause signal spikes due to reflections, depending on the surface properties and geometry of the object. In either case, for vehicle bumper heights below the critical height, the speed and length measurements will be incorrect because one or more of the vehicle edges will be incorrectly found.

An object that is lower than critical height cannot be detected by the system. When the bumper height of a vehicle is lower than the critical height, the detection results have an error in vehicle length. The value of the length error is $(L - l)/L$, where l is the length of the vehicle body at the critical height and L is the length of the vehicle (including bumpers). However, this error does not necessarily affect the vehicle reidentification because the detected lengths of a vehicle under different detectors are the same when the detectors at different locations have the same critical height.

When a vehicle moves into a detection zone, it blocks the laser from being received by the sensor. When the first beam is blocked, the current time is recorded. When the second beam is blocked, a second time is recorded. These times give the speed of the front of the car. In a similar manner, when each of the beams is no longer blocked, the times are recorded and the speed of the rear of the vehicle can be calculated. The time that each detector is blocked is also recorded and is used to calculate the vehicle length, assuming constant vehicle acceleration. The assumption of constant acceleration is valid for free-flow traffic conditions, where there is negligible acceleration, and for conditions where the vehicle is accelerating or decelerating uniformly during the time it is in the detection zone. These cover the majority of situations, but there are a few situations, such as stop-and-go traffic, where this basic detection method will not work well.

The system is easy to set up and calibration can be done in a few steps. After mounting the detector over the highway, each laser module is rotated so its reflected laser beam can be received by its sensor counterpart. If the mounting height is known ahead, this step can be omitted. After that, the opening of the aperture of the Tamron lens may need to be adjusted to ensure that the electrical output signals are in a reasonable range. Once these steps are done, calibration is automatically performed using electronics.

A. Laser and Electronic Systems

In the system, two laser lines are projected onto the road. In order to obtain high-resolution and high-reflection signals, the laser has to be well focused parallel to the vehicle velocity. The laser pulse, which is controlled by a driver, has to be stable in amplitude. The system has a peak power output of 20 W at 905 nm, with a pulse width of 15 ns. It can be pulsed at a maximum rate up to 10 kHz, without significantly reducing the power of individual pulses. The line-generating optics produces a beam with a full fan angle of 15–60°. Its high performance and small size make it a good candidate for use in the field deployable prototype system.

A wavelength of 905 nm for the laser was chosen for a number of reasons. Infrared light has good transmittance through fog, giving the systems better performance under a larger range of weather conditions. Furthermore, the intensity of sunlight around the wavelength of the laser is a local minimum, giving the system better rejection of noise due to sunlight. An infrared laser was also thought to be more appropriate for outdoor use because it is invisible to the human eye and would therefore cause no distraction to passing motorists. A band-pass filter matched to the wavelength of the laser is used to reduce the level of ambient light received by the sensor. With the assumptions that the laser is located 6 m above the roadway, the laser line is 5 m long and 5 mm wide, and that a potential observer is 2 m above the roadway, the laser is safe for viewing times up to 20 min, which is below the minimum ANSI laser safety standard by a large margin [12]. Although it is unlikely that a driver would stop on the highway and stare into the beam for this long, warning signs will be posted to prevent it.

The sensor optics consist of an imaging lens system and a telescopic lens system. The imaging lens system focuses the reflected laser light onto the active area of the sensor array. The imaging lens was selected based on the criteria that it should have an adjustable focal length within a range around the desired focal length, that it should have a field of view large enough to capture the width of an entire lane, and that it should be compact for easy integration into the outdoor system. We selected an off-the-shelf Tamron lens (Tamron 23VM816) as the imaging lens for our system. The reason to choose this product is that it has an adjustable focal length and has an adjustable aperture, which allows us to adjust the output signals of sensors to a desired level. The telescopic lens system is mounted in front of the imaging lens system. It is designed to restrict the field of view of the imaging lens along the width of the laser line, but not alter the field of view along the length of the line. Because the laser line is much longer than it is wide, the use of the imaging lens alone would result in a much wider strip of pavement being visible to the sensor than is desired. The telescopic lens system is used to match the dimensions of the laser line image with those of the sensor array. It consists of one positive and one negative planocylindrical lens. These two lenses are positioned to form a Galilean telescope. Since the ratio of the uncorrected field of view of the width of the sensor to the desired field of view is approximately equal to the ratio of the focal length of these two lenses, the focal length of lenses are chosen to make the resulting field of view of the width of the sensor to a desired value. A more detailed description of the optical system and the measurement principles can be found in [12]. The mechanical design of the optics for the prototype system is flexible and allows the optical components to be adjusted to optimize alignment and focus of the laser beam.

A 25-element avalanche photodiode (APD) array is used as the sensor in our detection system. The sensor converts the reflected laser light into a current signal. The sensor circuit is the main part of the electronic hardware in the detection system. In the field prototype, some low-cost high-speed amplifier chips with suitable bandwidths were chosen to meet the high demand for signal amplification. According to the principle of detection, the system needs only to distinguish if a vehicle is present or not under the laser lines. A multivibration monostable oscillator is triggered by the pulses from the amplifier and generates high-level output when there is no vehicle under the system. When the moving vehicle blocks the laser, there is no trigger pulse and the output will be low. Using a digital signal as output from the hardware will significantly simplify the signal processing in the software and reduce the data to be transferred and processed. The implementation of this method is based on the high signal-to-noise ratio of the new circuitry. The circuitry is based on simple, cheap, commonly available electronic components; thus, the cost of the new circuitry is very low. Because of the use of new components and advanced design, the electronic circuitry has a compact size. This makes it possible to place all amplifiers for 24 channels on a small printed circuit board without long connection wires. This is important because the signals from the photodiode array are very weak.

B. Data Acquisition and Signal-Processing Hardware and Software

A general purpose low-cost digital input/output (I/O) board PCI-DIO-96 from the National Instruments is used as an input interface between the sensor circuitry and the computer system. This digital I/O has 96 channels of configurable I/O; thus, it is suitable for our system when all 48 channels of signal are required.

Data acquisition software is used to collect, process, and display data from the hardware of the detection system. The

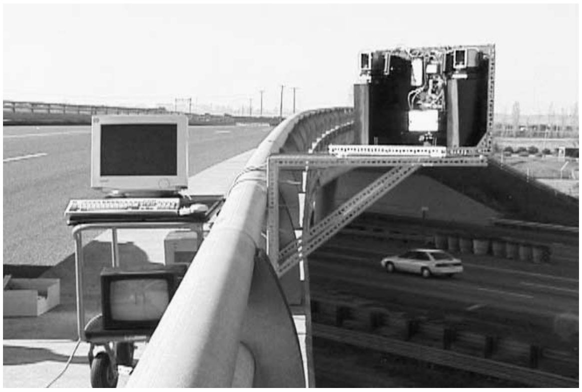

Fig. 2. Detection system mounted above the highway.

data are read from the output of sensor electronic circuit periodically. All tasks have to be done at the same time. However, the data are to be acquired in the same interval from the hardware. In other words, the data acquisition task should be deterministic, otherwise information will be lost. The concurrence of the deterministic tasks requires real-time performance of the operating system. In the present version of the measurement system, we have implemented the real-time detection software based on RT-Linux system [16].

III. Experimental Results

The detection system has been tested on a highway with real traffic, and experiments have been conducted to test operation of the system in different weather conditions and with different road materials. Fig. 2 is an image of the test site and the detection system mounted on a bridge across the highway.

In the present configuration, only 4 of 24 elements of each photodiode array were used for testing. The front and rear vehicle speeds, length, and acceleration were measured during the tests. The data acquisition rate was 10 kHz. Figs. 3–6 demonstrate typical signals and measurements of highway tests for various situations. Images of the vehicles are also placed in these figures for comparison.

The user interface window is shown on top of each figure. This window contains a menu bar, a status window, and a strip chart. The menu bar is used to control the system, i.e., to start or stop data acquisition and to set parameters of the system. The signals from the sensor electronic circuitry are displayed dynamically in the strip chart, which scrolls from right to left. The signal is at a high level when a vehicle is not present and changes to a low level when a vehicle blocks the laser. This transition occurs over a time that is much shorter than the sampling interval. Since all the signals are displayed at the same position, only one signal line can be seen on the chart when there is no vehicle or a vehicle blocks the laser lines. We can distinguish signals from different sensor elements when they change from low to high level at different times. The front speed v_1, rear speed v_2, acceleration a, and length l of the vehicle are displayed on the lower part of the window. Each line corresponds to one pair of sensor elements. Currently,

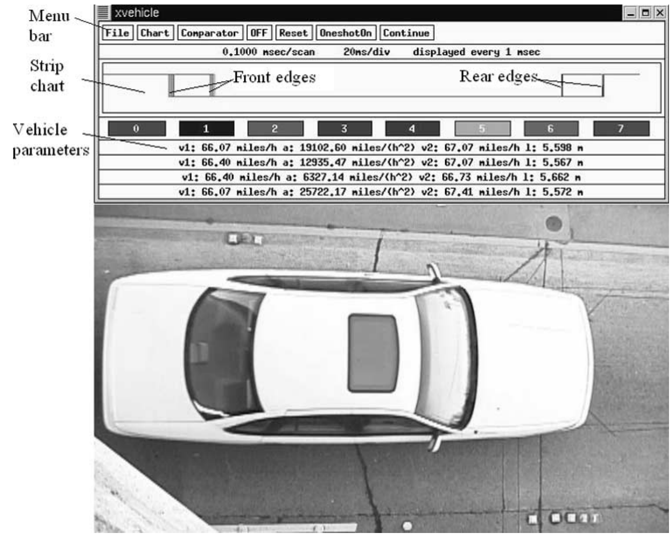

Fig. 3. Test results for a passenger car.

Fig. 4. Test results for a van.

we only display four pairs of sensor elements. As an example, in Fig. 3, the front speed, acceleration, rear speed, and length calculated from the first pair of sensor elements are 66.07 mi/h, 19 102.6 $\mathrm{mi/h^2}$, 67.07 mi/h, and 5.598 m, respectively (it is to be noted that $1\ \mathrm{m/s^2} = 8053\ \mathrm{mi/h^2}$). It is noted that equations and methodologies for calculation of velocity, acceleration, and length have been presented elsewhere [12].

As shown on the left side of the strip chart in Fig. 3, the transition edges for the vehicle front did not occur at the same time. The differences occur because of the curved front bumper on this vehicle. Different parts of the curved front bumper hit the laser beam (which is planar) at different times. On the other hand, the rear bumpers are essentially flat in this figure, and the transition edges for the rear bumpers (in the right side of strip chart) transit up at almost the same time. Similar trends were

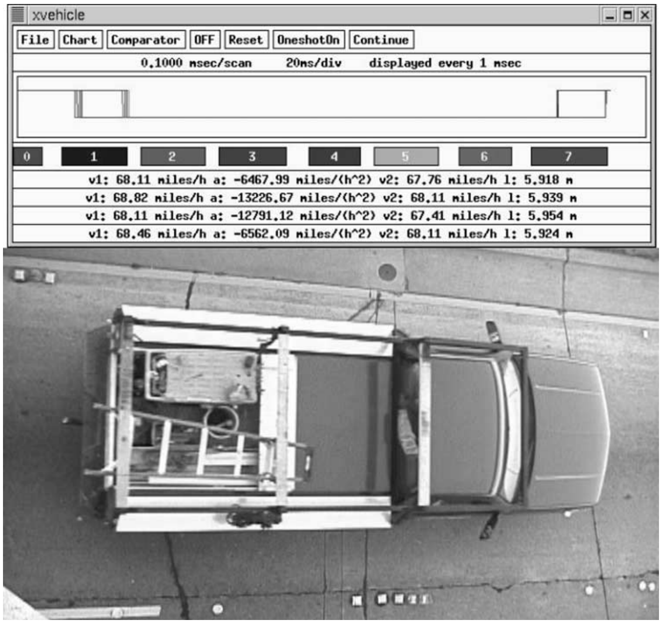

Fig. 5. Test results for a truck.

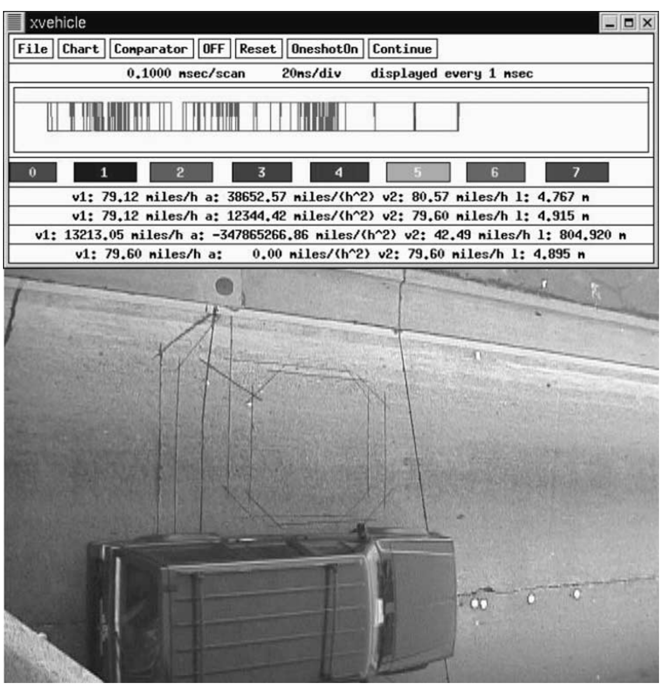

Fig. 6. Test results for a vehicle changing lanes.

also observed with other vehicles that had straight or curved bumpers (see Figs. 4 and 5).

Fig. 6 illustrates the signals when a vehicle was changing lanes. The vehicle did not block completely the signal in the left pair of sensor diodes; thus, there were many transitions in the signal for this pair (this pair corresponds to the third row of vehicle parameters). The vehicle parameters for other sensor pairs were still accurate.

These results show that the signals for the field prototype system are clear and the transition is fast enough for measurement. The system is consistent in measuring vehicle lengths and speeds. A vehicle traveling at a representative speed of 65 mi/h will cross the two laser lines in about 17.5 ms. As a result, the error caused by the sampling interval is less than about 1.14%. Misalignment of the laser lines on the road might also cause some errors, although such errors can be accounted through system adjustment and calibration. It is noted that the accuracy of our detector has been accessed during the development and field testing efforts. A separate journal paper that provides detailed information on measurement errors is available [17].

Experiments were also performed to assess the effects of ambient conditions on system performance. The detection system was mounted outdoors (at a UC Davis test site) for more than 24 h to test influences of temperature and weather on system performance. The analog circuit in the earlier version of the system was fairly sensitive to the environment. In the current implementation, the circuit consists of two parts. The first part is an analog circuit that amplifies the detected signal. The second part of the circuit converts the amplified signal to digital form. Since the digital circuitry is less sensitive to the environment and can usually operate over a wide temperature range, only waveforms and amplitudes of the analog signals in the system were recorded in our experiments. The data were acquired automatically by a computer at preset intervals. The signal amplitude and temperature data over a long-term test period in clear weather are shown in Fig. 7. The data were sampled every 5 min. As shown in Fig. 7, the signal amplitude mostly depends on the temperature. The short-term signal fluctuations in the figures are due to the variable nature of the pulsed diode laser, but we can still see the trend of a shift in signal amplitude as the temperature changes. There was a slight fog observed in the morning during testing, but it seems that it did not influence the signal amplitude. From Fig. 7, we can see that the signal amplitude increases when the temperature decreases. This is because the sensitivity of the photodiode array increases with lower temperature.

Fig. 8 shows further results from the environment tests. The data in this figure were obtained every 10 min. The effect of precipitation was minimal, and the signal level was mainly influenced by temperature, similar to the clear-weather results. Fig. 9 shows the noise levels during these tests. The noise varied over the range 0.07–0.1 V, which is about an order-of-magnitude smaller than the signal levels (see Figs. 7 and 8). Even if the signal fluctuation (noise level) is 0.5 V, the signal level is still adequate for triggering the digital output circuitry in a reliable fashion. It is noted that the present results on weather conditions were obtained under warm weather conditions available in California. It is planned that future quantitative studies will be performed to assess the impact of more severe weather conditions such as snow on the detection system.

Signal levels from reflection of the laser from different road materials have also been measured. Table I shows data for cement, aged asphalt, and new asphalt. The signal levels shown in the table are relevant values for comparison. The reflection from cement is higher than asphalt. Driveway patch was used as the new asphalt and might not be representative of real conditions

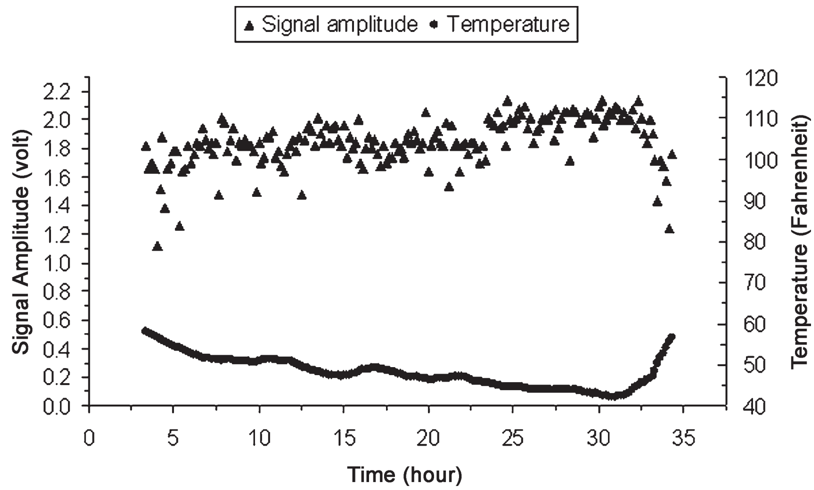

Fig. 7. Signal amplitudes for testing in clear weather.

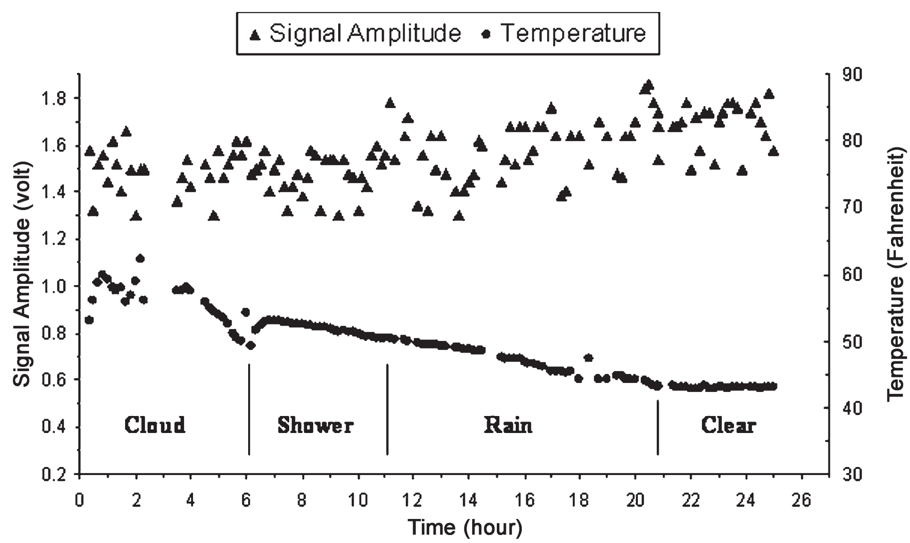

Fig. 8. Signal amplitudes for different weather conditions.

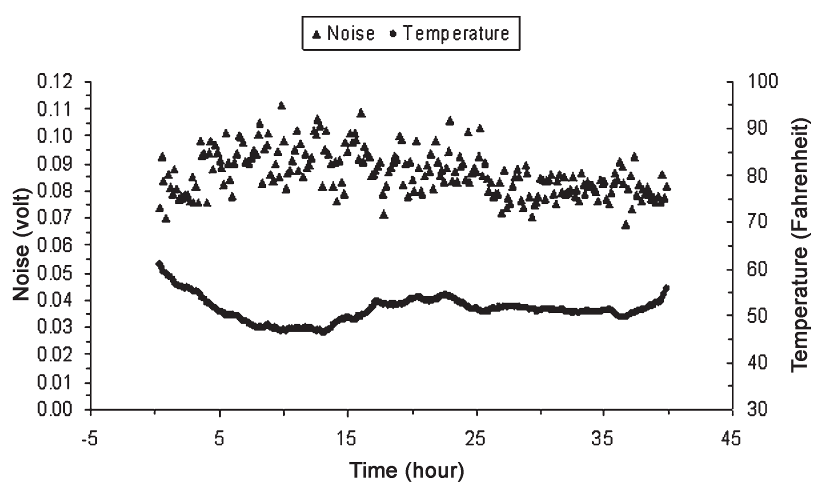

Fig. 9. Noise levels during an extended-time test.

TABLE I
COMPARISON OF SIGNAL LEVELS FROM DIFFERENT MATERIALS

Surface condition	Signal level (V)		
	Cement	Aged asphalt	New asphalt
Dry	1.89	1.46	0.588
Wet	>2.00	>2.00	0.86

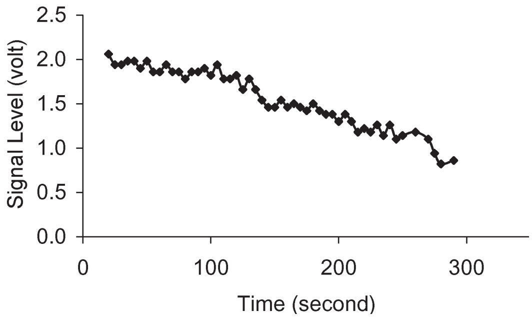

Fig. 10. Signal level vs. time after saturation of a new asphalt surface with water.

of asphalt used for road construction. Although reflection from this new asphalt is much lower than other material, our system can still obtain a signal level high enough for detection. Fig. 10 indicates the change of signal from the new asphalt when the surface was drying out. In the beginning when we poured water on the surface, the signal level was much higher and the amplifier was saturated. After about 5 min, the surface dried out naturally and the signal reached a more stable level that was about 40% higher than dry surface. In short, wet surfaces increase reflection. If the system works well for dry surfaces, it should have no problem to work for wet surfaces.

The distance between the laser system and the road determines the intensity of reflected laser light received by the sensors. We measured the signal level for different distances between the system and a reflecting surface in the laboratory. The reflecting surface material is new asphalt. For the system in which the optical system is adjusted to focus at a distance of 8.5 m, the signal level for different distances is shown in Fig. 11. The optical system was not adjusted when distance was changed. There is a maximum signal level around 6.5 m, because the signal level depends on two factors: the density of reflected laser and focusing of optics. The sensor received less reflected laser light when the system was moved away from the reflecting surface, and the signal level is lowered after 6.5 m because the image of laser line on the sensor became blurred. For distances less than 4 m, increases of signal due to the close distance overcame reductions of signal caused by the blurred image. Therefore, the system should be aligned for the actual mounting height before it is mounted on the highway and the height should be as low as possible to obtain a better signal level. The higher the system mounted on the highway, the lower the signal level is. However, the minimum height is limited by the required space between road and detection system. Normally, the system should be mounted at a height of 7–9 m.

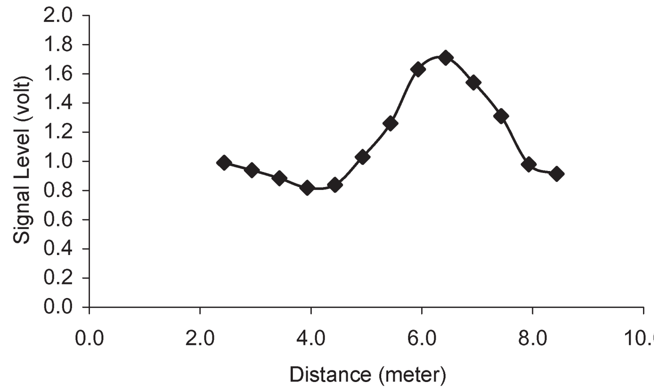

Fig. 11. Signal level vs. distance between the laser system and a reflecting surface.

It is also noted that the system did not appear to be sensitive to vibration. This is likely a result of the mechanical construction of the system in that both laser modules and the optical system are mounted on the same sturdy platform and would vibrate in the same way. During field testing when the detector was mounted on a highway overpass, vibrations caused by passing trucks did not seem to have a noticeable effect on the detection results. Nevertheless, we intend to perform thorough quantitative studies on the effects of vibration on our detection system with quantitative data in the future, and the results will be reported at a later date.

IV. CONCLUSION

This paper presents results from a new version of a laser-based real-time, nonintrusive detection system for measurement of true travel time of vehicles on the highway by identifying the delineations of moving vehicles. The system has been tested on the highway with real traffic and the results indicate that this measurement methodology can achieve high accuracy for vehicle identification. Further test results for different weather conditions and road materials show that the system is suitable for operation on the highway. Data pertaining to a detected vehicle can be saved with a time stamp to a disk in real time or can be transmitted via network to a host machine in a control center for further processing to obtain travel time information. Based on the present test results, we believe that the proposed method will provide detailed information on travel time which can be used to help travelers infer future states of the transportation system.

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