TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

IDEA *Innovations Deserving Exploratory Analysis Program*

INTELLIGENT TRANSPORTATION SYSTEMS

Report of Investigation

The ITS-IDEA program is jointly funded by the U.S. Department of Transportation's Federal Highway Administration, National Highway Traffic Safety Administration, and Federal Railroad Administration. For information on the IDEA Program contact Dr. K. Thirumalai, IDEA Program Manager, Transportation Research Board, 2101 Constitution Avenue N.W., Washington, DC 20418 (phone 202-334-3568 fax 202-334-3471).

IDEA PROJECT FINAL REPORT
Contract ITS-6

IDEA Program
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LASER VEHICLE DETECTOR-CLASSIFIER

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INNOVATIONS DESERVING EXPLORATORY ANALYSIS (IDEA) PROGRAMS MANAGED BY THE TRANSPORTATION RESEARCH BOARD (TRB)

This investigation was completed as part of the ITS-IDEA Program, which is one of three IDEA programs managed by the Transportation Research Board (TRB) to foster innovations in surface transportation. It focuses on products and results for the development and deployment of intelligent transportation systems (ITS), in support of the U.S. Department of Transportation's national ITS program plan. The other two IDEA programs areas are TRANSIT-IDEA, which focuses on products and results for transit practice in support of the Transit Cooperative Research Program (TCRP), and NCHRP-IDEA, which focuses on products and results for highway construction, operation, and maintenance in support of the National Cooperative Highway Research Program (NCHRP). The three IDEA program areas are integrated to achieve the development and testing of nontraditional and innovative concepts, methods, and technologies, including conversion technologies from the defense, aerospace, computer, and communication sectors that are new to highway, transit, intelligent, and intermodal surface transportation systems.

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EXECUTIVE SUMMARY

This report describes a diode-laser-based vehicle detector and classifier (VDAC) developed by Schwartz Electro-Optics (SEO) under the Transportation Research Board (TRB) Intelligent Vehicle-Highway Systems (IVHS), now Intelligent Transportation Systems (ITS), Innovations Deserving Exploratory Analysis (IDEA) Program. The VDAC uses a scanning laser rangefinder to measure three-dimensional vehicle profiles that can be used for accurate vehicle classification. The narrow laser beam width permits the detection of closely spaced vehicles moving at high speed; even a 2-in.-wide tow bar can be detected. The VDAC shows great promise for applications involving electronic toll collection from vehicles at freeway speeds, where very high detection and classification accuracy is mandatory.

The extensive network of modem highways in the United States today offers a fast, safe, convenient means of transporting goods and people within and between the major cities of the country. However, the U.S. highway system is under considerable stress. The traffic congestion that currently pervades metropolitan areas threatens future gridlock if mitigating steps are not soon taken. According to ITS America (I), "The percent of peak hour travel on urban interstates that occurred under congested conditions reached 70 percent in 1989, up from 41 percent in 1975 ." If this trend continues, all peak-hour traffic will be congested by 2000; there is good reason to believe that the trend will **continue.** FHWA data show that since about 1965 the number of vehicle miles traveled has been increasing at a faster rate than expenditures on highway maintenance and that total capital spending for highways, streets, roads, and bridges has declined by more than 50 percent. It is assumed that the growth in traffic and decline in new roadway construction will continue and that a worsening traffic congestion problem can be expected.

One of the goals for ITS in the United States is to reduce congestion. Through areawide traffic management, ITS can use existing facilities to improve traffic-flow efficiency. Advanced sensor technology is needed to provide accurate, real-time traffic-parameter data, such as volume, occupancy, speed, and classification, which are required to optimize the performance of areawide traffic management systems. Information on real-time traffic conditions can be used for rapid incident detection and en-route driver navigation.

The sensors of choice for many future ITS applications will undoubtedly be mounted overhead. Although inductive loops are simple, low-cost devices, they are not as easily installed or maintained because of their in-pavement location. Several types of overhead vehicle detectors are being developed (2), including video detection systems, microwave radar detectors, ultrasonic detectors, passive infrared sensors, and active infrared sensors. Of these, only the active infrared sensor, using a laser rangefmder, has the capability for accurate vehicle profiling as a result of the narrow angular beam width of the laser. This profiling capability, a dual-beam configuration that permits speed measurement, and efficient vehicle-recognition software combine to produce a sensor that can classify vehicles as well as measure their presence and speed. The outstanding utility of such a sensor became good motivation for its development as a practical device.

VDAC relies on an inherent laser characteristic-narrow angular beam width--to provide the high resolution required for accurate vehicle, profiling. The VDAC beam-scan geometry is shown in Figure 1. The

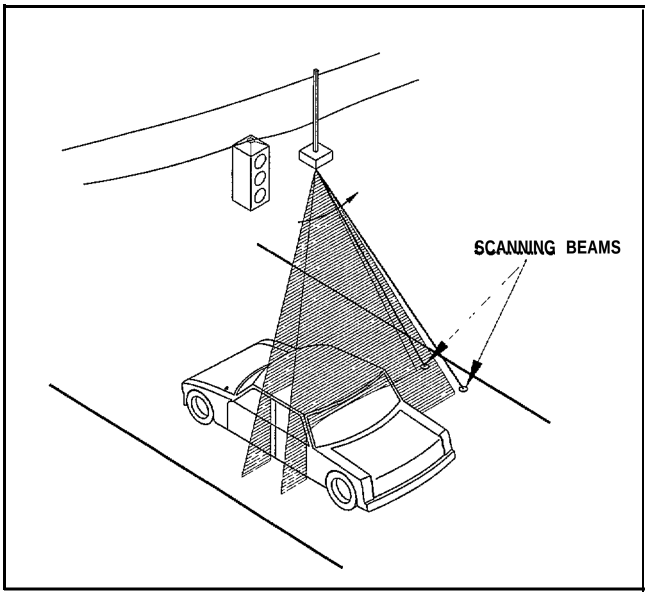


FIGURE 1 VDAC beam-scan geometry.

system scans two narrow laser beams, at a fixed angular separation, across the width of a lane at a rate of up to 720 scans/sec. Pulsed time-of-flight range measurements provide accurate (± 3 in.) transverse height profiles of a vehicle on each scan. The vehicle speed, determined from the time interval between the interceptions of the two laser beams by the vehicle, is used to space the transverse profiles appropriately to obtain the full three-dimensional vehicle profile. An algorithm similar to those developed for military target recognition is applied to the three-dimensional profile for vehicle-classification purposes.

An example of the VDAC three-dimensional profiling capability is provided by the range image shown in Figure 2. This range image of a van pulling a boat traveling at a speed of 45 mph was obtained by the VDAC operating with a scan rate of 360 scans/sec. The pixel spacing resulting from the l-degree scan resolution is more than adequate for vehicle identification.

VDAC uses a rotating polygon as shown in Figure 3 to line scan a diode-laser rangefmder across a 12-ft-wide lane of highway. The polygon scanner rotates continuously in one direction at a constant speed. The angle between each facet and the base of the polygon alternates between 87.5 and 92.5 degrees for adjacent facets; as a result, successive scans are made with an angular separation of 10 degrees, which provides the two separate beams needed for speed measurements. As shown in Figure 4, the 0.5- by 12-mrad laser beam illuminates a 5- by 120-mm spot on the pavement that provides good m-lane resolution and optimum cross-lane coverage when the laser is pulsed once per degree of scan angle.

Applications for VDAC are many and include the following:

- Vehicle classification for toll charging.
- Use with wireless smart cards to prevent cheating by verifying vehicle classification.
- Vehicle road location and timing determination for license plate photography.
- Wide-area real-time surveillance for signalized intersections and freeway monitoring.
- Traffic parameter measurement such as average speed, road occupancy, traffic count by type of vehicle, and queue length at lights.
- Very accurate vehicle presence detection.
- Vehicle height measurement for bridge, tunnel, or overpass warning.
- Road and freeway accident detection by traffic speed measurement.
- Temporary emergency replacement for disabled in-pavement inductive loops.
- Operation where inductive loops are impractical: bridges, parking garages, or cobblestone or brick streets.

PROBLEM STATEMENT

Because ITS is such a new program, a set of precise requirements for VDAC does not exist. The first several months of the project were used to establish these requirements through the aid of a vehicle sensor survey and phone conversations with potential users. After the survey results were analyzed, a detailed product design specification was generated.

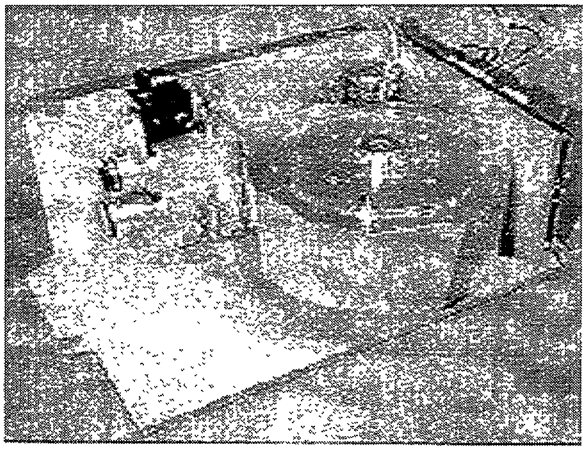


FIGURE 3 VDAC hardware showing rotating polygon.

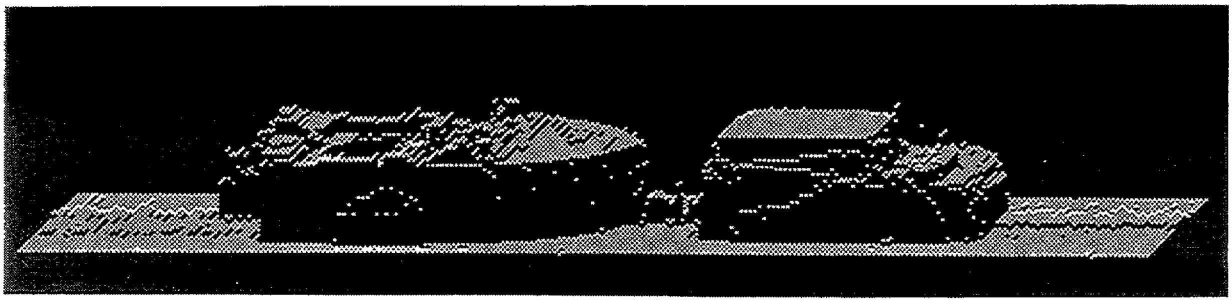


FIGURE 2 Three-dimensional range image of a van pulling a boat.

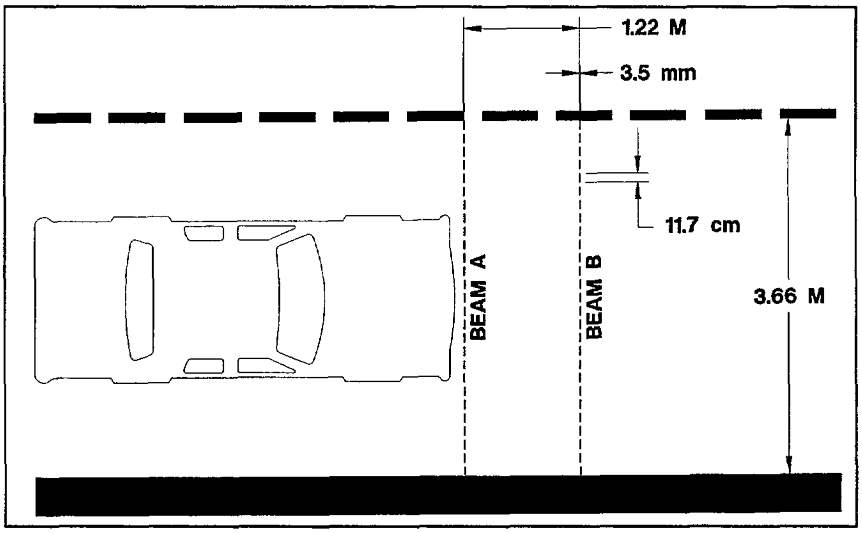


FIGURE 4 Laser beam footprints on road surface.

VEHICLE-SENSOR SURVEY

The purpose of the user survey was to develop a set of requirements based on the following:

- Requirements met by current sensors.
- Requirements not met by current sensors.
- Future requirements.
- Specific functional and operational requirements such as number of vehicle classes, classification accuracy, operating voltage, data interface, mean time between failures (MTBF), and so forth.

The vehicle-sensor questionnaire was mailed to 80 prospective vehicle-sensor users. (A copy of the questionnaire is included as Appendix A.) The mailing list for the survey was selected from the Council on IVHS listed in the Institute of Transportation Engineers Directory and from previous SEO contacts. Twenty-six of the questionnaires were returned. Survey data were entered on a spreadsheet where the results could be analyzed. Each of the 36 entries from the 26 questionnaires was graphed in a histogram similar to that shown in Figure 5.

The results in Section 1 of the survey indicated that detecting presence, measuring speed, separating closely spaced vehicles, and vehicle classification were important to most of those responding. Detecting vehicle height, length, and width individually was judged less important by most of the respondents although it was important to a few and is vital to the classification algorithm. Detecting tow bars was important to 15 percent of those surveyed, which included all those needing sensors for electronic toll collection. Multiple-lane coverage was important to most users, but may be a difficult requirement to meet with a single sensor.

Section 2 of the survey asked for specific requirements for detection accuracy, speed-measurement accuracy, number of vehicle classes, and classification accuracy. Detection-accuracy responses ranged from 95 to 100 percent, with most between 98 and 99.9 percent. Speed-accuracy responses ranged from 1 to 5 mph, with most from 1 to 2 mph. The number of vehicle classes required ranged about equally from 3 to 16. Classification-accuracy responses ranged from 50 to 99.95 percent, with most in the 90 percent range.

Sections 3 and 4 asked the potential user to rate the importance of several functional and operational features. Responses indicated that users consider ease of installation, an enclosure approved by the National Electrical Manufacturers Association (NEMA), and microprocessor control to be desirable features. There was a unanimous response that reliability is of the highest importance.

Section 5 of the survey asked for specific requirements for detection response time, MTBF, and data interface. Detection-response-time requirements varied from 1 to 10 msec. MTBF requirements varied from 2 to 7 years, with the most common response of 5 years. The most commonly required data interfaces for VDAC were the presence relay and the RS232 serial computer interface. RS422 (differential serial computer interface) and optically isolated solid-state relays were also selected. The relay output is used to indicate vehicle presence and can also be used as an accurate (<5 msec) rear-of-vehicle camera trigger.

Section 6 asked for specific requirements for ambient temperature range, shock, and vibration. Responses for ambient temperature range varied from minus 40° to 0° C for cold and from 40° to 85° C for hot. There were only two responses for the shock and vibration requirements, indicating their low importance.

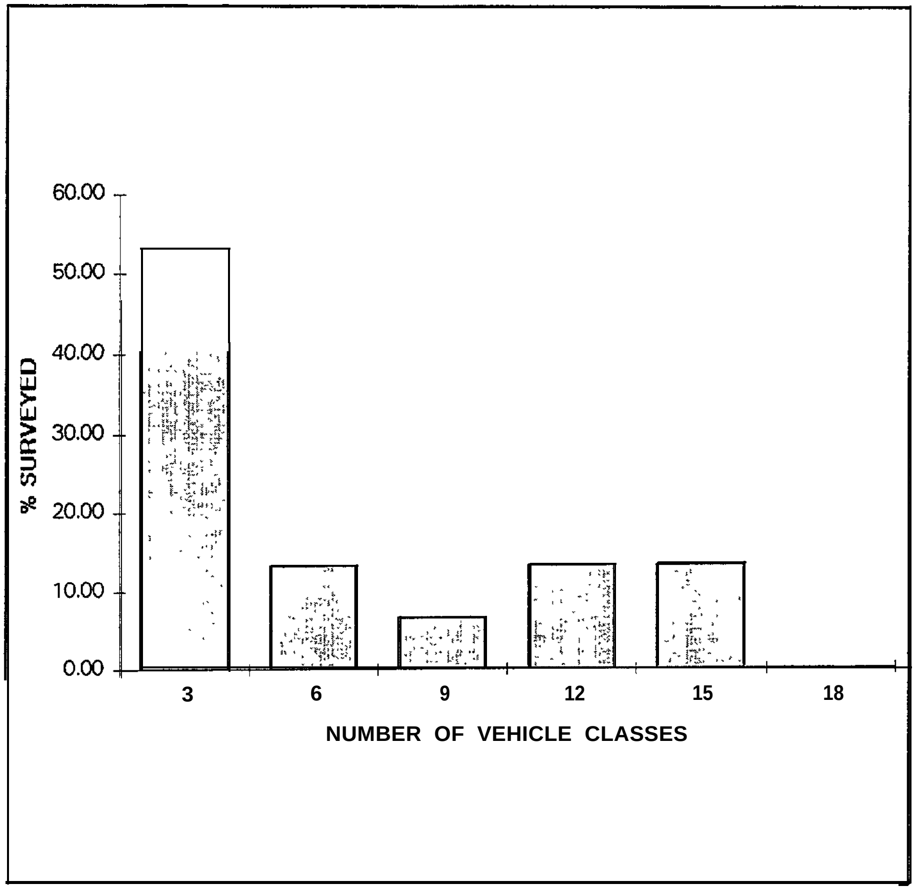


FIGURE 5 Example histogram showing number of vehicle classes required.

The survey revealed that the most common VDAC requirements not satisfied by current sensors are vehicle separation and classification, particularly under high-volume, high-speed traffic conditions. Survey responses indicated interest in the following areas of application (in order of interest): (a) traffic data collection, (b) traffic signal control, (c) temporary installations, and (d) electronic toll collection. For the most part, it was not possible to categorize questionnaire response according to application area because respondents indicated an interest in more than one area. This was not true for the electronic toll collection area, however, which was of singular interest in three of four cases (e.g., Hughes Transportation Management Systems, Amtech Systems Corporation, and MFS Network Technologies). These potential VDAC users want sensors that are very accurate (99.9 to 99.9999 percent detection accuracy, 95 to 99.95 percent classification accuracy), highly reliable, and have a long lifetime (2.3 to 5 years). They are concerned about the effect of environmental conditions on sensor performance, particularly weather (rain, fog, snow) and temperature (minus 40^0 to 85^0 C). On the basis of their need for high detection and classification accuracy, the electronic toll collection companies appear to be prime customers for VDAC systems.

PRODUCT DESIGN SPECIFICATION

The product design specification presented in Table 1 was established on the basis of (a) the results of a vehicle-sensor survey implemented via questionnaires mailed to potential VDAC users, (b) discussions with major ITS companies (e.g., MFS Network Technologies and Hughes Transportation Management Systems), and (c) previous SEO experience in developing diode-laser-based vehicle sensors.

RESEARCH APPROACH

A schematic diagram of the VDAC system is shown in Figure 6. The VDAC's laser rangefmder uses an InGaAs diode-laser transmitter and a silicon avalanche photodiode (APD) receiver in a side-by-side configuration. The transmitter consists of the diode laser and its driver circuit and a collimating lens. The optical receiver is composed of an objective lens, narrow-band optical filter, detector-amplifier, and threshold detector.

The laser diode used in the VDAC is an InGaAs injection laser diode having 12-W output at 10 A pulsed current drive. The laser driver produces a 10-A peak current pulse with a 3-nsec rise time and an 8-nsec pulse

TABLE 1 VDAC Specifications

SCAN RATE	360 SCANS / SEC / BEAM
FIELD-OF-REGARD	30”
SCAN RESOLUTION	1”
BEAM SEPARATION	IO”
RANGE MEASUREMENTS PER SCAN	30
MAXIMUM RANGE	50 FT
MINIMUM RANGE	5 FT
RANGE ACCURACY	3 IN
RANGE RESOLUTION	3 IN
INTERFACE	RS422, RS232 SOLID STATE RELAY- PRESENCE LOGIC-LEVEL (l-l-L) PRESENCE
LASER BEAM GEOMETRY	IN-LANE AXIS - 0.5 mrad CROSS-LANE AXIS - 16 mrad
LASER WAVELENGTH	904 nm
LASER EYE SAFETY	“EYE SAFE” IN COMPLIANCE WITH 21 CFR 1040 CDRH
POWER SUPPLY VOLTAGE	115VAC, 24VDAC
TEMPERATURE RANGE	-40^{o} C TO 60^{o} C
VEHICLE CLASSIFICATION	11 CLASSES
SPEED ACCURACY	SPEED DEPENDENT (see Appendix B)

width. A trigger pulse from the scanner control circuit triggers the laser at the proper scan angles. The 904-nm laser emission is at an ideal wavelength for the silicon APD receiver used.

The optical detection circuitry converts optical radiation reflected from the vehicle and road to, first, an equivalent electrical analog of the input radiation and, finally, a logic-level signal. The logic-level signals are processed within the range counter logic to yield analog range data, which are read by the microprocessor.

An analog range-measurement technique was chosen for VDAC because of its better resolution, smaller size, simpler circuitry, lower power consumption, and lower cost when compared with digital techniques. The analog range measurement circuit, know as a time-to-amplitude converter (TAC), has an accuracy of 1 percent of measured range and a resolution of plus or minus 3 in. TAC uses a constant-current source to charge a capacitor to obtain a linear voltage ramp whose instantaneous value is a measure of elapsed time. The circuit is designed so that the voltage across the range measurement capacitor begins ramping down from the positive power supply when the laser fires. The ramp is stopped when either a reflected pulse is received or the end of the measurement period is reached. The TAC output is then converted to digital by a fast 1 O-bit analog-to-digital converter.

The VDAC software processes the range data and outputs vehicle classification, vehicle speed, and so forth, via a serial interface to a remote computer. The major software functions are identified in the block diagram shown in Figure 7. The algorithms that must be implemented for each function were developed and tested, to some extent, in previous projects. The vehicle detector and speed calculator are used in SEO’s Autosense I unit. The real-time range loop, calibration, and gain adjustment routines have been used in several other projects. The vehicle profiler and vehicle classifier are related to algorithms that have been designed and tested under military research programs. The VDAC rule-based classification algorithm will classify the 11 different types of vehicles shown in Figure 8.

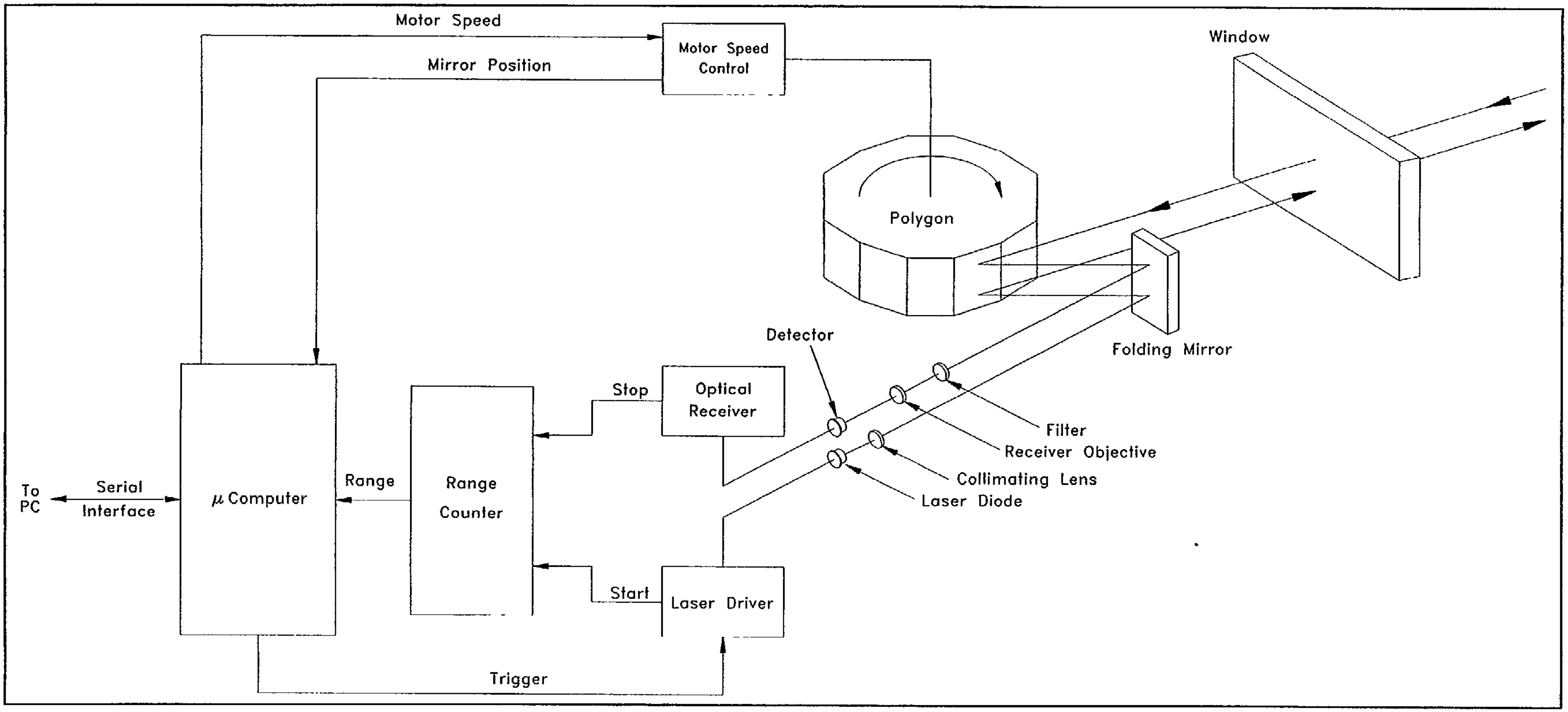


FIGURE 6 VDAC system schematic diagram.

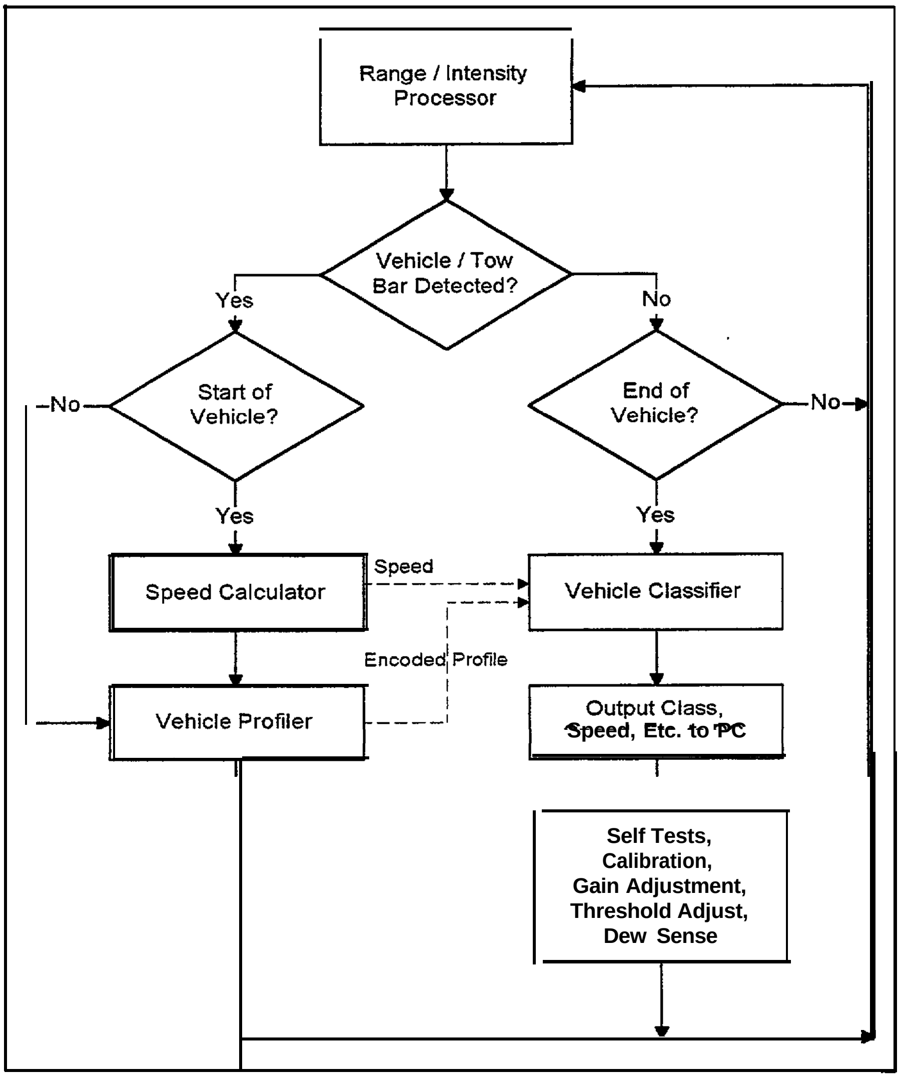


FIGURE 7 Block diagram for major VDAC software functions.

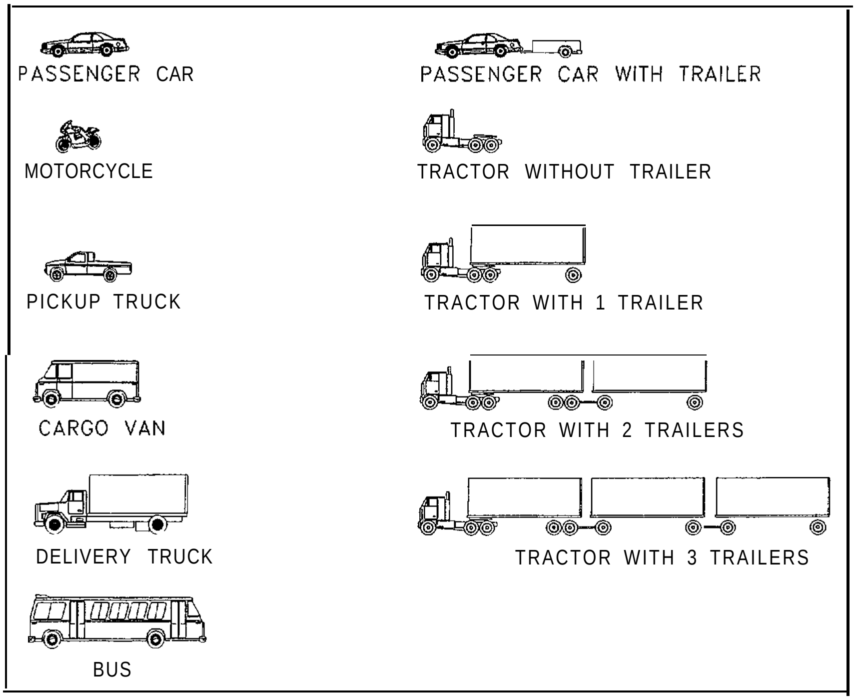


FIGURE 8 Eleven vehicle types classified by VDAC.

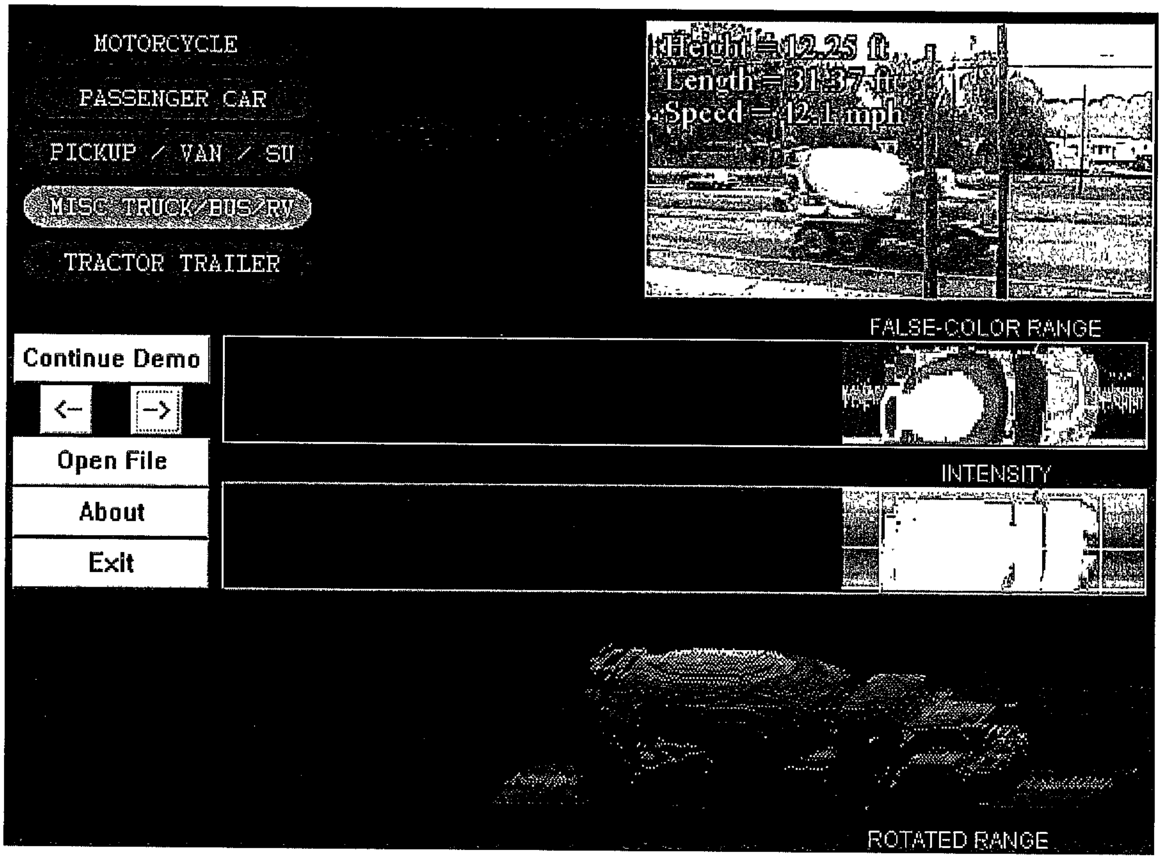
Range data are used by the vehicle detection algorithm to determine when a vehicle is present. The vehicle detection algorithm first calculates the range to the road and then sets a threshold above the road that is used to determine the presence of a vehicle. A certain number of consecutive range samples above the detection threshold are required to accurately detect the presence of a vehicle and reduce false alarms.

RESULTS

SE0 tested VDAC at a site in front of the SE0 facilities on Florida SR 441. VDAC was mounted to a mast arm extending over the curb lane of this major arterial as shown in Figure 9. Testing was carried out 24 hr/day for an extended period of time. This permitted testing under varied traffic conditions, including peak-hour, off-peak, and stop and go, and under varied environmental conditions such as rain, fog, and high temperature.

During testing, the VDAC algorithm was modified as required to optimize vehicle detection and classification capabilities. The program code was uploadable to VDAC via the serial interface, making possible the real-time optimization of VDAC performance.

FIGURE 9 VDAC mounted on mast arm.



Height = 12.25 ft
Length = 31.37 ft
Speed = 12.1 mph

FIGURE 10 Computer display of real-time VDAC classification data.

The vehicle profiles were collected and organized in a data base. By using the data base, specific vehicle types were extracted and used for vehicle-classification algorithm development. After the classification algorithm was developed, a search of the data base provided data from similar vehicles for classification algorithm testing. The data base contains fields that include vehicle class, height, length, speed, and so forth, corresponding to each vehicle detected. A video image was captured and stored for each vehicle for easy verification of the vehicle-classification algorithm. A computer display of VDAC classification data, including vehicle profile and video image, is shown in Figure 10. Approximately 1,200 vehicles per hour can be verified using the data base display software. Currently 50,000 vehicles are logged in the data base.

Tests performed have included detection accuracy, classification accuracy, and speed accuracy. Detection of 100 percent was visually confirmed in a test of 10,000 vehicles. The detection accuracy tests were performed in fair weather with some light rain and therefore the accuracy might degrade some during extended tests or during severe weather conditions. Classification accuracy of 95.5 percent for 10 vehicle classes was achieved using the 50,000~vehicle data base. The confusion matrix (Figure 11) shows the classification results for the 50,000 vehicles. The top matrix shows the vehicle count and the bottom matrix the percentage of classification. The numbers along the diagonal of the bottom matrix show the percentage of classification for each vehicle class. Off-diagonal numbers show the possibility of confusion between specific vehicle classes. For example, 5.04 percent of pickups were confused with passenger cars. The overall percentage of classification for all vehicle classes is shown in the lower right corner of Figure 11.

CONCLUSION

Schwartz Electra-Optics has developed a diode-laser-based vehicle detector-classifier that can accurately detect and classify vehicles moving at freeway speeds. Several major ITS companies have expressed a desire to purchase VDACs when they become available for electronic toll and traffic management (ETTM) applications. Such applications require sensors that are very accurate and highly reliable and have a long lifetime. SEO is confident that VDAC will prove useful for traffic surveillance and signal control as well as ETTM applications.

VDAC may find its first implementation as part of the Toronto Highway 407 project for Hughes Traffic Management Systems, where 300 to 400 VDACs will be used as part of a completely automated overhead toll collection system. In this ETTM application VDAC is required to provide accurate vehicle detection, classification, separation, lane position, and camera trigger information to the roadside toll collection system. Production of VDACs for this project was to begin in the last quarter of 1995.

GLOSSARY

Camera trigger-a signal generated by the VDAC when it detects the end of a vehicle. This signal can be used to trigger a video camera to capture an image of the vehicle's license plate.

Classification-the capability of differentiating among types of vehicles.

Detection-the ability to sense that a vehicle, whether moving or stopped, has appeared in the detector's field of view.

Detection response time-the time it takes to sense that a vehicle is in the detector's field of view.

Electronic toll collection-the completely automated process of billing on toll roads using electronic communication with the vehicles.

Laser-a device that amplifies light and produces an intense monochromatic beam.

Scan resolution-the angle between successive range measurements.

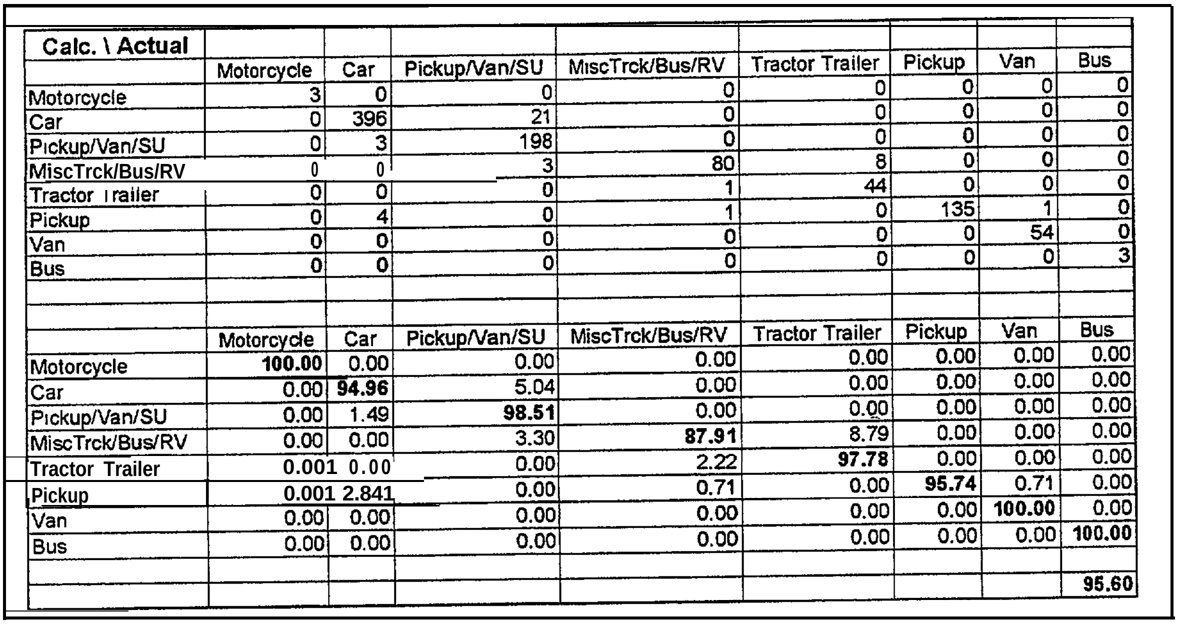
Separation-the ability to detect closely spaced vehicles as individual vehicles.

Transverse height profile-the height profile measured across the vehicle from side to side.

REFERENCES

1. *Strategic Plan for intelligent Vehicle-Highway Systems,* Report ITS-AMER-92-3. ITS America, Washington, D.C., 1992.

2. Kell, J.H., I.J. Fullerton, and M.K. Mills. *Traffic Detector Handbook,* 2nd ed. Report FHWA-IP-90-002, U.S. Department of Transportation, July 1990.



Calc. \ Actual	Motorcycle	Car	Pickup/Van/SU	MiscTrck/Bus/RV	Tractor Trailer	Pickup	Van	Bus
Motorcycle	3	0	0	0	0	0	0	0
Car	0	396	21	0	0	0	0	0
Pickup/Van/SU	0	3	198	0	0	0	0	0
MiscTrck/Bus/RV	0	0	3	80	8	0	0	0
Tractor Trailer	0	0	0	1	44	0	0	0
Pickup	0	4	0	1	0	135	1	0
Van	0	0	0	0	0	0	54	0
Bus	0	0	0	0	0	0	0	3

	Motorcycle	Car	Pickup/Van/SU	MiscTrck/Bus/RV	Tractor Trailer	Pickup	Van	Bus
Motorcycle	**100.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Car	0.00	**94.96**	5.04	0.00	0.00	0.00	0.00	0.00
Pickup/Van/SU	0.00	1.49	**98.51**	0.00	0.00	0.00	0.00	0.00
MiscTrck/Bus/RV	0.00	0.00	3.30	**87.91**	8.79	0.00	0.00	0.00
Tractor Trailer	0.001	0.00	0.00	2.22	**97.78**	0.00	0.00	0.00
Pickup	0.001	2.841	0.00	0.71	0.00	**95.74**	0.71	0.00
Van	0.00	0.00	0.00	0.00	0.00	0.00	**100.00**	0.00
Bus	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**100.00**
								95.60

FIGURE **11** **Vehicle classification confusion matrix.**

APPENDIX A:

VEHICLE-SENSOR SURVEY

Currently used sensor(s)

TYPE______________________________________

REQUIREMENTS MET___________________________

REQUIREMENTS NOT MET_______________________

FUTURE REQUIREMENTS________________________

Application

☐ Traffic signal control
☐ Traffic data collection
[] Electronic toll collection
☐ Temporary Installations
[] Other______________________________________

CHARACTERISTICS DESIRED IN VEHICLE DETECTOR/CLASSIFIER

1. Please rate the importance of these functional characteristics:

	LOW						HIGH
DETECT VEHICLE PRESENCE	1	2	3	4	5	6	7
MEASURE VEHICLE SPEED	1	2	3	4	5	6	7
MEASURE VEHICLE HEIGHT	1	2	3	4	5	6	7
MEASURE VEHICLE LENGTH	1	2	3	4	5	6	7
MEASURE VEHICLE WIDTH	1	2	3	4	5	6	7
VEHICLE CLASSIFICATION	1	2	3	4	5	6	7
SEPARATE CLOSE-SPACED VEH	1	2	3	4	5	6	7
DETECT TOW BARS	1	2	3	4	5	6	7
MULTIPLE LANE COVERAGE	1	2	3	4	5	6	7

2. Please specify requirements for:

DETECTION ACCURACY________________________________

SPEED MEASUREMENT ACCURACY________________________

NUMBER OF VEHICLE CLASSES___________________________

CLASSIFICATION ACCURACY_____________________________

---

3. Please rate the importance of these features:

	LOW						HIGH
EASE OF INSTALLATION	1	2	3	4	5	6	7
OVERHEAD MOUNTING	1	2	3	4	5	6	7
SIDE-FIRE MOUNTING	1	2	3	4	5	6	7
NEMA-APPROVED ENCLOSURE	1	2	3	4	5	6	7

---

4. Please rate the importance of these operational features:

	LOW						HIGH
MICROPROCESSOR CONTROL	1	2	3	4	5	6	7
TIME-TAGGED DATA	1	2	3	4	5	6	7
RELIABILITY	1	2	3	4	5	6	7
SELF TEST	1	2	3	4	5	6	7

---

5. Please specify requirements for:

DETECTION RESPONSE TIME__________________________

MTBF____

INTERFACE

Cl Relay Output

Cl RS232 Port

☐ RS422 Port

☐ **Other**______________________________________

6. Please specify required environmental conditions:

AMBIENT TEMPERATURE RANGE____________________________

SHOCK____

VIBRATION____

7. Please circle the appropriate value for these general characteristics:

PRICE	1	2	3	4	5	6	7	8	9	10	K$
SIZE	200	400	600	800	1000						m^3
WEIGHT	2	4	6	8	10	12	14	16	18	20	lb
POWER	1	2	3	4	5	6	7	8	9	10	W

120 VAC 24VDAC 12VDAC OTHER

Additional Comments:

APPENDIX B:

VEHICLE SPEED AND LENGTH MEASUREMENT ACCURACY

Vehicle speed is determined by measuring the time interval (Δt) between the interceptions of two laser beams a known distance (w) apart using

$$V = w / \Delta t \qquad (1)$$

If the absolute error in Δt is δt and the absolute error in w is δw, the absolute error in V is given approximately by

$$\delta V \approx \frac{\partial V}{\partial(\Delta t)}\delta t + \frac{\partial V}{\partial w}\delta w \qquad (2)$$

$$\delta V \approx \frac{w}{(\Delta t)^2}\delta t + \frac{1}{\Delta t}\delta w \qquad (3)$$

Since $\Delta t = w / V_{\text{actual}}$,

$$\delta V \approx \frac{\delta t\, V_{\text{actual}}^2}{w} + \frac{\delta w\, V_{\text{actual}}}{w} \qquad (4)$$

Thus, the error in speed has one component proportional to V^2 and another proportional to V.

An exact calculation of the error in speed yields

$$\delta V = \frac{w \pm \delta w}{w / V_{\text{actual}} \pm \delta t} - V_{\text{actual}} \qquad (5)$$

Most of the δt error is due to the ± one-scan-period uncertainty in laser beam interception and is given by the reciprocal of the scan rate. For example, for a 12-sided mirror configuration rotating at 60 rps, the scan rate would be 12 x 60 = 720 scans/sec. If the beam were deviated through an angle θ on alternating beams to effectively generate a pair of beams, A and B, separated by a distance w at the road surface given by

$$w^2 = R_A^2 + R_B^2 - 2\, R_A R_B \cos\theta \qquad (6)$$

where R_A and R_B are the ranges to the road surface along each beam, then the effective scan rate for each beam would be one-half of the dual-beam scan rate, or 360 scans/sec, and $\delta t = 1/360 = 2.77$ msec. Assuming a ±3-in. range-measurement accuracy, the sensor mounted 23 ft above and pointed straight down at the roadway, $\theta = 10$ degrees, and a vehicle detection threshold of 1.5 ft, Equation 6 can be used to calculate $w = 3.6$ ft and $\delta w = \pm 0.044$ ft. Substituting these values into Equation 5 and calculating δV for a speed of 100 mph:

$$\delta V = \frac{3.6 \pm 0.044}{3.6 / 88 \pm .00277} - 88 \qquad (7)$$

and δV varies from -5.5 to 6.4 mph. This function produces a nonlinear relationship between the instantaneous vehicle speed and speed error as shown in Figure 12.

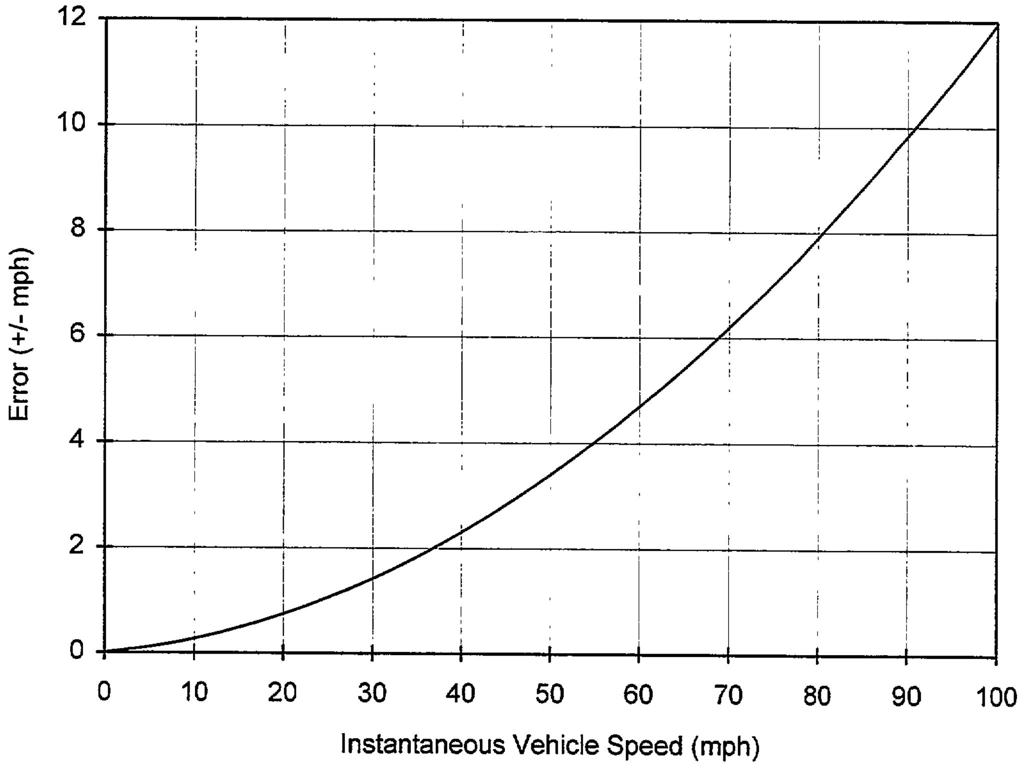


FIGURE 12 Speed error dependence upon vehicle speed.

The random laser-beam interceptions that occur within the ± one-scan-period uncertainty result in a statistical distribution of the measured values of speed. We assume that a normal distribution applies to the values of speed measured by Autosense. The distribution is given by

$$Y = \frac{1}{\sigma\sqrt{2\pi}} e^{-(\delta V)^2 / 2\sigma^2} \qquad (8)$$

where Y is that fraction of the total number of measurements having a given variance δV from the actual value, δV is the difference between the measured speed value and the actual value, and σ is the standard deviation, which describes the breadth of the distribution of deviations from the actual values—68.3 percent of δV values are within one standard deviation of the actual value. If the values given by Equation 7 are correlated with the breadth of the distribution at $3.3\sigma =$ (99.9 percent of δV values are within 3.3 standard deviations of V_{actual}), then $\sigma = 1.5$ mph. Now if n measurements of a velocity v, which has σ value = 1.5 mph, are averaged, the σ of the average is reduced by the square root of n so

$$\text{avg } \sigma(v) = \frac{\overline{\sigma(v)}}{\sqrt{n}} = \frac{1.5 \text{ mph}}{\sqrt{n}} \qquad (9)$$

if $n = 10$, then avg $\sigma(v) \approx 0.47$ mph. So clearly average speed measurement will be accurate to ± 1 mph.

Vehicle length is determined by counting the number of scans detected on the vehicle and multiplying this scan count by the calculated speed and the scan-to-scan time. Because the calculated speed is used to determine the vehicle length, length measurement has the same speed-dependant accuracy as speed.