Trial Implementation of a Photoelectric Sensor System To Classify Vehicles

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The development and field testing of an automatic vehicle classification (AVC) system in 1990 and 1991 are described. The system employs an inductance loop detector and a pair of photoelectric sensors emitting modulated infrared-spectrum light beams, which are reflected off raised pavement markers. The presence of a vehicle activates the loop detector, prompting the system to classify the passing vehicle. The pattern of the infrared light beam interruptions enables the system to infer the vehicle's speed, number of axles, and number of tires. The number of axles and tires defines the vehicle's class for assessing the proper toll. Signals from the activation go through a special microprocessor into a personal computer for interpretation, display, and recording. The system was tested initially at a high-speed (50 to 65 mph) Oklahoma Turnpike Authority site. Evaluation of the computer records and written field notes obtained during a 5-wk study indicated that the first-generation AVC system correctly classified about 95 percent of the 1,736 vehicles observed. After a review of the data and the number and type of errors found therein, it was concluded that the system software could be modified to correctly classify about 97 percent of the vehicles. The AVC system was subsequently modified and installed in four automatic vehicle identification toll-gate lanes on the Turner and Will Rogers turnpikes in Oklahoma, where vehicles with a special device on board are allowed to debit their toll account as they pass through without stopping. Evaluation of the AVC system operating in this environment is continuing.

Several different types of traffic data are needed for planning, designing, and operating street and highway systems. One such type of data are vehicle classification data, which report the number of various types of vehicles in the traffic stream. Some classification methods aggregate vehicle types into groups or classes according to the number of axles and the tire arrangement, whereas others use different criteria.

In the past, human observers have been the predominant means by which to obtain vehicle classification data. Development of mechanical or automated systems to do this job may lower data-collection costs while improving data accuracy and reliability.

This paper describes the conceptual development and field evaluation of an automatic vehicle classification (AVC) system in 1990 and 1991. The Oklahoma Turnpike Authority (OTA), wanting to deploy an AVC system to enhance their toll collection and auditing operations, contacted the Center for Transportation Research at The University of Texas at Austin and the Oklahoma Transportation and Infrastructure Center at The University of Oklahoma concerning the development of such a system. The recommended system employs an inductance loop detector and a pair of photoelectric sensors emitting infrared-spectrum light beams, which are reflected off raised pavement markers (RPMs) of the type commonly used to mark traffic lanes. The RPMs are positioned near the middle of the lane, so the tires of passing vehicles will straddle the RPMs. The presence of a vehicle activates the loop detector and prompts the system to classify the passing vehicle into one of eight classes in the OTA toll schedule. When a vehicle straddles the RPMs, each of the tires on one side will for an instant interrupt the pair of infrared beams. The pattern of the interruption of the infrared light beams enables the system to infer the vehicle's speed, number of axles, and number of tires; thus, its class. Signals from the activation go through a special microprocessor into a personal computer for interpretation, display, and recording.

The initial charge to the development team was to recommend an AVC system for application in a manually operated toll gate situation in which vehicles stop—sometimes more than once—and then pass through the gate area at slow speeds, probably while accelerating. Later, the objective was shifted to developing an AVC system that would function in a toll collection lane in which vehicles pass through the toll gate—perhaps at medium to high speeds—without stopping. This system was envisioned for possible application in toll collection lanes designated for vehicles equipped with automatic vehicle identification (AVI) devices.

The higher-speed AVC system was built and field tested during the summer of 1990 on the Turner Turnpike east of Oklahoma City, where traffic speeds were about 50 to 65 mph. These tests indicated promising performance from the system and suggested software modifications that would improve the accuracy of vehicle classification.

In late 1990 and early 1991, specially designed hardware and software were installed at four AVI-equipped toll collection lanes on the Turner and Will Rogers Turnpikes between Oklahoma City and the Missouri state line. Evaluation of these systems, operating in an environment in which vehicle speeds are generally about 25 to 40 mph, is progressing. Continuing observations have identified problems not encountered during the initial tests. Means of addressing these new problems are being considered and developed.

BACKGROUND

OTA has operated six toll roads in the state of Oklahoma for a number of years; four new roads are now opening. There are about 100 toll gates. The amount of the toll charged to a

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vehicle is determined by the classification of that vehicle and the distance traveled. Classification is determined by the number of axles and tires per vehicle. There are eight vehicle classes:

Class 1. Automobile, motorcycle, or two-axle, four-tired truck;
Class 2. Class 1 vehicle towing one-axle trailer;
Class 3. Class 1 vehicle towing two-axle trailer;
Class 4. Two-axle bus, or two-axle, six-tired truck;
Class 5. Three-axle bus, or single/combination three-axle truck;
Class 6. Four-axle combination truck;
Class 7. Five-axle combination truck; and
Class 8. Six-or-more-axle combination truck.

The Need

Until 1991, OTA's toll collection system relied on the toll booth attendant to correctly classify vehicles and assess the proper toll. A treadle in each toll lane provided an axle count to verify the attendants' totals. Manual auditing of this system was costly and time consuming. The treadles occasionally required maintenance.

OTA wanted to take advantage of current technology and upgrade the established methods of vehicle detection, vehicle classification, assessing tolls, collecting tolls, and auditing toll collection. A number of considerations prompted the decision to investigate new AVC technology. Because public expectations of governmental agency accountability are continually rising, OTA felt a need to upgrade the means of auditing toll collections. In short, OTA had decided to aggressively pursue new technology to make its operation more efficient.

AVI Toll Collection System

OTA introduced systemwide automatic toll collection on January 1, 1991. The automatic toll collection system was based on AVI system technology. Motorists who wish to participate purchase a debit account. When they do, they get a transponder tag the size of a deck of playing cards. This tag is attached with removable adhesive strips to the inside-front windshield of the vehicle.

The AVI system employs a transmitter and receiver at each toll collection station. The signal sent by the transmitter is altered by the transponder tag inside each subscribing vehicle and reflected to the receiver. Subscribing vehicles do not stop to pay tolls at booths with AVI equipment. Instead, the account of the participating vehicle is automatically debited as the vehicle passes through the toll-assessing area (i.e., the toll gate).

Each AVI account is "classification specific." That is, the user of an AVI tag is supposed to use that tag only in a vehicle of a certain classification. For instance, an AVI tag purchased for an automobile (Class 1) is not supposed to be used with an automobile pulling a trailer (Class 2) or in a tractor-semitrailer truck (Class 7), because the toll for a Class 1 differs at a given toll booth from the toll for a Class 2 or a Class 7.

While finalizing plans for installation of the AVI system, OTA decided that an AVC system should complement the automatic toll collection system. Used in the toll collection environment, automatic vehicle classification data can

1. Verify each manual vehicle classification made by toll collector;
2. Audit the automatic vehicle classification of each tagged vehicle, to determine whether the proper tolls were being assessed; and
3. Override the AVI tag signal to correctly charge a vehicle with an incorrect tag in the windshield.

Thus, AVC was needed to complement both manual and automatic toll collection operations.

Initially Recommended AVC System

In early 1990, before actually implementing the AVI system, OTA contracted with the Center for Transportation Research at The University of Texas at Austin and the Oklahoma Transportation and Infrastructure Center at The University of Oklahoma to conduct a feasibility study and suggest a method that could automatically classify vehicles at manually operated turnpike toll gates. The study (*1*) reported some methods that were currently under development or in use on other toll systems, such as those using ultrasonic detectors. The study recommended an AVC system using a pair of photoelectric sensors and an inductance loop vehicle presence sensor; this system was then under development at The University of Texas at Austin (*2*).

Later in 1990, the Turnpike Authority modified its original intent and requested the demonstration of an AVC system for use in a nonstop, higher-speed environment. The researchers recommended the same basic sensor array for this application and proceeded to develop hardware and software for demonstration at a high-speed sight.

INITIAL DEVELOPMENT AND TESTING

The recommended system was a "first-generation" concept and therefore needed additional testing and modification before being ready for full-scale implementation. The system was tested from mid-August to mid-September 1990 on the west end of the Turner Turnpike (I-44), northeast of Oklahoma City. The test was conducted in the right, or outside, lane only; vehicles in the left lane were not classified.

Procedure

The researchers conducted seven tests over a period of about 5 wk. Each test lasted no more than a few hours during daylight. The tests were conducted in warm to hot weather. There was no rain during any of the tests.

The system hardware included the modulated infrared light beam sensors, a loop detector, raised pavement markers, a special microprocessor, a microcomputer, and wiring. In addition, housing is needed to protect the sensors and the computers from the elements. Two adjacent steel pillbox-like cylinders with lids served as housings for the infrared sensors. The pillboxes were positioned beside the shoulder, shielded

by an existing guardrail. The pillboxes were less than a foot high and about a foot in diameter. Both pillboxes had portholes with visors, to allow the infrared beam to be sent and received. Figure 1 shows a schematic layout of parts of the initial system.

The main goal of the test was to evaluate the system's ability to correctly classify passing vehicles according to the OTA toll classification scheme. To accomplish this, human observers classified passing vehicles just before the vehicle entered the location where automatic classification was to occur. The human observer orally communicated his or her classification to a person at a microcomputer keyboard, who in turn entered the observer's classification as the automatic classification was taking place. Researchers decided to employ two persons (observer and keyboarder) instead of one so the observer would not have to look away from the road and because physical constraints at the sight (such as electric power availability and the limited view of lanes from a narrow embankment) made it undesirable to try to classify from the spot where the computer was located. The recording procedure created a computer file with both the observer's record and the automatic record stored together. Later, these records were compared to determine the number and nature of differences between the observer and the AVC system. Another person at the test site recorded any observer or keyboard input errors, so when the record was reviewed later, it would be easier to separate human errors from automatic system errors.

Problems and Solutions

There were some computer and software problems during the first few tests. The problems were identified and solutions

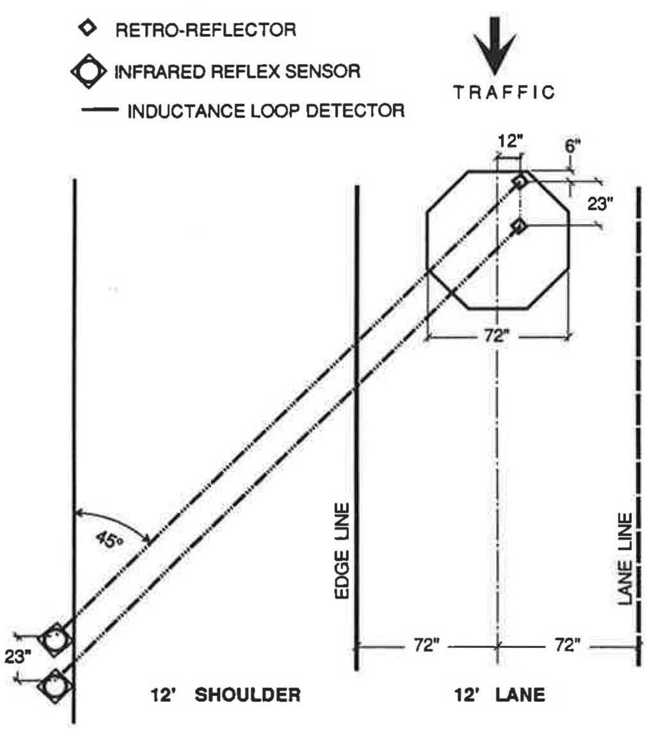

FIGURE 1 AVC sensor arrangement for initial high-speed tests.

implemented, so the system functioned well during the later tests. There were also human-input errors, especially when a number of closely spaced vehicles came by. With less than 2-sec headways, it was difficult to correctly key in the vehicle class before a following vehicle passed by the loop and sensors.

In addition to computer problems, the researchers had to find an ideal spacing between the sensors. The system sometimes confused wide single tires with narrow dual tires. During the latter data-taking sessions, the AVC system occasionally indicated, in a seemingly random pattern, dual tires on the front axle. For a dual tire to be indicated, both infrared light beams must have been interrupted simultaneously. The cause of this problem was not obvious. Cleaning the lenses did not alleviate the problem. Eventually, researchers decided that the dimensions of some wide single tires and some narrow dual tires were too similar.

A few vehicles did not straddle the RPMs but instead passed by entirely to the right or to the left of them. All four tires of the few passenger cars that traveled to the extreme right side of the instrumented lane interrupted the infrared light beams. Vehicles positioned in this manner registered "extra" axles because four tires interrupted the infrared beams, not two. The AVC system had difficulty classifying motorcycles. Some motorcycles came by in pairs, pulled small trailers, or passed by to the left of the reflectors.

Results

By reviewing the computer record, researchers were able to classify errors as caused by either human input, AVC-system error, or "unsure." The automatic vehicle classification system correctly classified about 95 percent of the 1,736 passing vehicles.

Some errors occurred when following vehicles were closely spaced; close headways create a need for a fast-executing program. The AVC system did not accurately classify motorcycles, and motorcycle detection problems accounted for 0.4 percent of the system errors.

The nature of the problems experienced was such that it was expected that some of the problems with the first-generation system were correctable, and it was estimated that the AVC's accuracy could be improved to about 97 percent. The testing of the first-generation AVC system led to the identification of issues that needed to be addressed during future research and development of the AVC system.

DEVELOPING AVC SYSTEM FOR IMPLEMENTATION

The Turnpike Authority notified the researchers in late 1990 that they had decided to implement the tested system on a small scale at four of the highest-volume toll plazas and wanted the system installed by early 1991. These sites are at each end of the Turner and the Will Rogers Turnpikes, which together extend from Oklahoma City northeast to the Missouri state line near Joplin, Missouri.

Each of the four plazas has one AVI lane, in which motorists with the proper AVI tags can proceed without stopping

to manually pay a toll. Vehicle speeds in the AVI lanes generally range from 25 to 40 mph. Infrequently, a motorist without an AVI tag, apparently unfamiliar with the system and not comprehending the meaning of the numerous signs, gets into the through-AVI lane and then comes to a stop, trying to find someone to whom to give a toll.

Designing the System

The researchers had only a few weeks to prepare for installation. Experiences from the initial system testing prompted some changes in the hardware and software installed at the four sites. The design configuration was also constrained by the existing layout of the toll plaza areas.

The toll plaza areas consisted of a number of islands in parallel, to channel all vehicles alongside one of the toll booths where collections were made. The newly created through-AVI lanes were located on the left or inside. To the left of the AVI lane is a median barrier curb, about 30 in. high. To the right of the AVI lane is an island and a tollhouse serving the lane to the right of the AVI lane. The tollhouses are enclosed, except for an open window through which the driver passes cash to the attendant. A crash attenuator is located in advance of the island and tollhouse.

An initial challenge was identifying a suitable location for the sensor installations, out of traffic. There was a space of about 4 to 5 ft between the backside of the crash attenuators and the front nose of the islands, with guardrail at the face of the lane. This location offered just enough space for a roadside sensor installation, so none of the island had to be jackhammered out.

The researchers chose not to use two pillboxes to house the infrared sensors as was done in the initial test. Instead, a single low-profile aluminum box was fabricated to house both sensors in one unit. This allowed the proper spacing between the sensor pairs to be set in the factory, as opposed to trying to correctly position them during a field installation. Based on previous experience, a 24-in. spacing between sensors was used. Visors projected inward into the aluminum box, so nothing protruded outside the box.

The widths of the AVI lanes varied among the four sites. The two sites on the Will Rogers had lanes approximately 10.5 ft wide; Figure 2 shows a schematic layout used on the Will Rogers sites.

The lanes on the Turner Turnpike were approximately 14 ft wide. The 14-ft widths posed a problem: that is, vehicles have more latitude than normal in the path taken as they pass through the loop and sensor area. The researchers needed to find a simple configuration that would detect vehicles anywhere within the lane, no matter how far to the left or to the right the vehicle was. The vehicle detection has to be made before the front tire interrupts the leading infrared beam, and the detection must continue until the rear tire has completely crossed the path of the trailing infrared beam. One constraint was keeping the loop relatively small so as to retain the ability to continually sense the presence of high-body trailers. In addition, researchers wanted to minimize the number of loops to simplify installation.

The researchers addressed this problem by employing a diagonal "figure 8" detector loop. The relative positions of

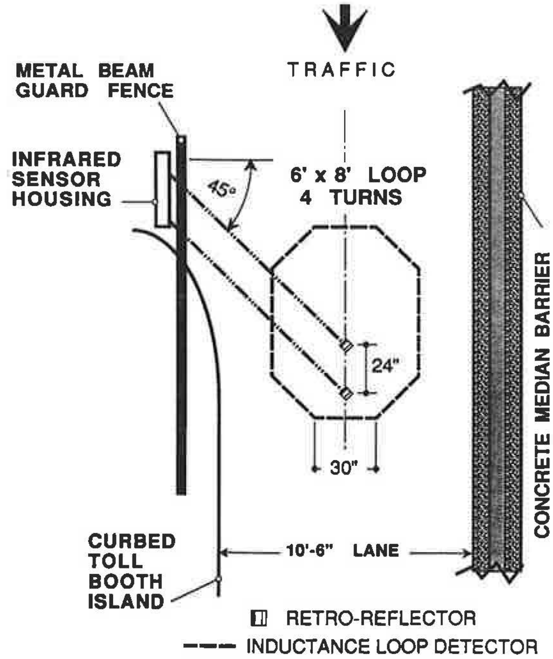

FIGURE 2 AVC sensor arrangement for narrow AVI lane.

the sensors, the reflectors, and the loop permit a vehicle in the right side of the lane to pass over the loop in time to activate the "call for detection" before the right front tire interrupts the leading infrared light beam. A vehicle at the extreme left side of the lane will still be over the other end of the figure 8 until after all tires have cut the trailing light beam. Figure 3 shows this layout. The reflectors were placed

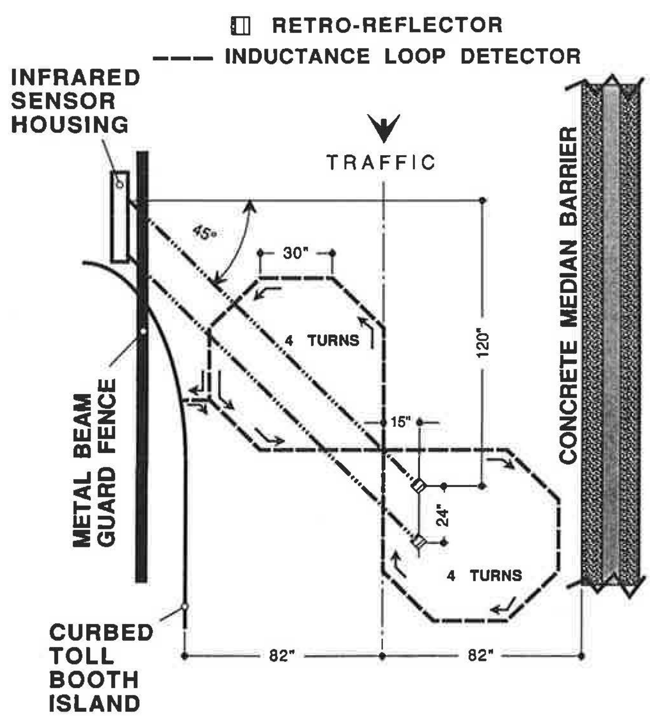

FIGURE 3 AVC sensor arrangement for wide AVI lane.

to the left of the lane centerline, in the hope that most motorcycles would pass to the right side of the reflectors, so the tires would interrupt the infrared light beams and be classified.

The researchers modified the original software so data collection could continue for a number of days before the data had to be downloaded. They also addressed the problem encountered during the initial test of confusing wide single tires with narrow dual tires. The solution was assuming that all front tires were single tires and then referencing following tires to the front tires. If the following tires were wider than 1.2 times the front tire width, the following tires were said to be dual tires. Width was inferred from the duration of infrared beam interruption.

Installing the System

The system was installed during the winter, with subfreezing temperatures often encountered. The cold weather influenced the researchers to use a poured asphalt adhesive to install the raised pavement marker reflectors in the lanes, as well as to attach the aluminum sensor housing boxes to the concrete surface. Wiring extended from the sensors, through previously installed conduit, into the nearest tollhouse, in which the microprocessor and microcomputer were housed.

Figure 4 shows a pair of sensors installed in the aluminum box; the box cover has been removed. Figure 5 shows the box in the background and the reflectors and loop in the foreground.

The loop and reflectors were located slightly upstream of the tollhouses. Any passenger car or other short vehicle in the AVI lane that erroneously stops alongside the tollhouse to pay a toll will have already left the detector loop before coming to rest. All four systems were turned over to the Turnpike Authority in working order.

MONITORING AND FURTHER DEVELOPMENT

OTA planned for the toll collection staff to check the AVC system performance. The other regularly assigned tasks prevented toll personnel from checking the system as often as needed, so monitoring was irregular. From available data, it was apparent the system was having problems, but there was not enough constant monitoring to identify the causes. It seemed that the problems could be arising from a combination of human input error and system malfunction.

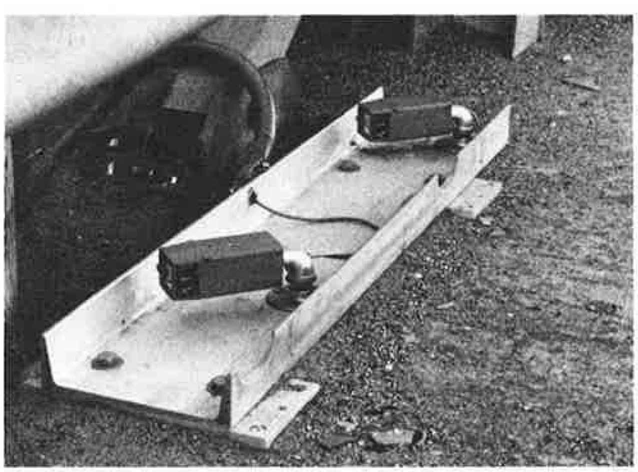

FIGURE 4 AVC sensors attached to base of box.

FIGURE 5 Loop, reflectors, and sensor housing box.

In summer 1991, two students employed by OTA for the summer assumed the task of monitoring the system. With regular field monitoring, and some intensive field checking, researchers think they have identified a number of problem causes.

A snowplow accidently removed the raised pavement markers during a late winter storm at the state line site. This site was the most time consuming to check, because for the person coming from Oklahoma City, it required another 3 hr of driving time past the third site. OTA decided not to reinstall the markers and to use the remaining three sites for evaluation and development.

Symptoms of Problems Encountered

There were many system problem symptoms. An AVC installation would appear to correctly classify for a few days, then have a few hours of obviously incorrect data. This period sometimes would be followed by apparently correct operation. Incorrect data took the form of a "Class 0" (i.e., AVC could not recognize a vehicle type) or unreasonably high speeds (i.e., 9,530 mph), or both. Sometimes the system would prematurely cease operation, and some data files contained more than one day's data (a mistake). There also had been some visible physical damage to the system wiring at one site.

Most of the observed classifications have been correct. In an exception, researchers observed the effects of a truck trailer having rear mud flaps that were dragging the ground. The flap touching the pavement surface interrupted the infrared beam, creating the impression of an extra axle. This caused the system to incorrectly classify a Class 7 as a Class 8 vehicle.

Attempts To Correct Problems

Many of the malfunctions happened with no one present to document a cause. From conjecture, researchers created a

list of potential problem causes. They were

- Infrared beam misalignment;
- Dirty reflectors;
- Pavement vibration;
- Human operator errors when downloading data and restarting system;
- Computer hardware problems; or
- Computer software problems.

A number of separate actions have been implemented in an attempt to improve the AVC system operation.

To eliminate operator input error as a source of problems, the computer keyboards were removed from the toll plazas. The keyboards are taken to the sites only by central office personnel. This action seemed to eliminate the problem of one file containing more than one day's data.

Researchers traced the root of some problems to equipment malfunction. Specifically, the microprocessor experienced electrical troubles. The cause could have been improper handling of the unit. The dirty environment is suspected as the cause of another computer malfunction, the failure of one floppy disk drive to copy. Computer covers had been installed over the front of the units, but the researchers making field visits often found them removed.

In the summer of 1991, one of the infrared sensor housing boxes came loose from the concrete pavement. The field monitors noted that they could reposition it and align the sensors, and then the system would correctly work until one or two heavy trucks passed by. The truck vibration caused the infrared beams to go out of alignment and no longer be reflected back to the unit for processing.

Suspected Chief Problem

The chief problem seems to be one of infrared beam reflection. After anywhere from 18 hr to a few days, the reflector surfaces of the raised pavement markers become coated and need a quick wiping. It was found that a product that "cuts" oil is better for this task than a window cleaning product. This problem was not encountered during the 5-wk test of the initial system. One difference is that the initial test site was at an unconfined location. At the toll plazas, there are structures, the median barrier curb, and highly channelized traffic. There may be fewer deposits and more natural cleansing at unconfined sites.

There also have been instances of the beam losing proper alignment. When this happens, the photoelectric emitting/receiving device has to be realigned or retargeted onto the RPM for the AVC system to resume operation.

If the trailing reflector is dirty or the trailing infrared beam is misaligned, then an unreasonably high-speed reading results. The series of events during this malfunction is as follows: vehicle interrupts leading beam at time t; trailing beam is not being successfully reflected, so computer reads this beam as being interrupted also at time t—the distance between the infrared beams traversed in an infinitesimally short time yields a high speed.

The current suspicion is that premature operation cessation resulted from an overloaded computer buffer. A series AVC system readings giving unreasonably high speeds and numbers of axles could overload the buffer. On encountering an operation cessation, the field monitors have sometimes found that simply cleaning the RPM reflective surface will allow the system to commence operation without any computer input. At other times, the computer system has to be restarted.

It seems that after a few months on the road, the reflectors are not as effective; the cause of this is not certain. At one site, the reflector had deteriorated after 5 months until the beam aimed at the marker could not be reliably received for more than a few minutes. The installation of new raised pavement markers in August 1991 seemed to address the problem. A second site is showing characteristics of the same problem. The computer software was modified to check for loss of infrared signal reflection, so malfunctions resulting from this cause could be identified with certainty.

AVC Operation During Rain

By chance, it rained during an August 1991 field check when the researchers were present. This gave the researchers an opportunity to assess the system operation during moderate precipitation. It appeared that spray from vehicle tires has the effect of interrupting the infrared light beam, which can distort the classification. For instance, the AVC system may incorrectly evaluate the infrared beam interruption pattern generated by a Class 7 truck and semitrailer as a Class 1 vehicle because the spray from the front tire blocked the beam until the first pair of dual-axle tires crossed the path of the beams. This extended interruption also created a very large front tire dimension in the computer memory, so the following dual tires appeared to be single tires. The distance between the front dual-tandem axle and the rear dual-tandem axle was such that the beam interruption ceased before the rear dual-tandem tires crossed the beam, although spray caused the rear tandem tires to be viewed as only one axle. The system would identify a slower-speed Class 7 as a Class 5 vehicle. The slower vehicle produces less spray, so the classification distortion is not as great.

Researchers observed one occurrence of the unaware driver stopping in the AVI lane to pay a toll, with another vehicle following closely. The impatient following vehicle was so close that the loop detector apparently did not differentiate between the two vehicles and recorded them as one Class 4 vehicle.

Additional Actions To Address Problems

The recent field monitoring has led to identification of other actions that may solve the observed problems. The following actions are now being considered.

1. Designing a custom raised pavement marker. Most of the marker body would be solid, but a slight recess would be formed in the side toward the sensor. The reflector would reside in the recess, which would permit a reflector surface to be covered from the top but exposed for reflection from the side.

2. Creating a larger RPM reflective surface. This could help improve reliability. A larger vertical dimension would allow the infrared beam to avoid losing alignment.

3. Modifying the computer logic to overcome the spray problem in wet weather. The vehicle speed is determined when the front tire interrupts the two infrared beams. Once the speed is known, then a duration for which a passenger car would occupy the loop can be estimated. If a loop occupancy duration exceeded the maximum for a car at that speed, then the vehicle classification would be "other than a Class 1." Because present experience shows that most users of the AVI system, indeed most vehicles on the turnpikes, are either Class 1 or Class 7, it is of some benefit to differentiate between Class 1 and "others," although it is still desirable to correctly identify all eight classes.

CONCLUSION

Evaluation of this AVC system using an inductance loop detector and a pair of photoelectric sensors emitting infrared light beams reflected off raised pavement markers is continuing. Recent observations have identified problems not encountered during the initial tests. Means of addressing these new problems are being considered and developed.

Recent testing has revealed that some vehicle classifications may be distorted when a layer of water covers the pavement surface. The apparent effects of tire spray blocking the light beams constitute a significant system limitation. Computer programming techniques may partially overcome this problem. In many areas rainfall occurs only a small fraction of the time, so this limitation may be tolerable for many AVC system applications.

If system modifications can eliminate other problems and lead to creation of an AVC system that will operate reliably with minimal maintenance, then the next step would be to link the AVC input with elements of the AVI system and other OTA toll collection operations. This AVC system may have other practical classification applications as well.

ACKNOWLEDGMENT

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