ELECTRONIC TOLL COLLECTION:
FIELD PERFORMANCE EVALUATIONS

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prepared by
Center for Urban Transportation Research
College of Engineering
University of South Florida

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TABLE OF CONTENTS

GLOSSARY OF TERMS ........................................ 5

I. EXECUTIVE SUMMARY ..................................... 11

II. PURPOSE AND SCOPE .................................... 12

III. BACKGROUND ............................................. 13

IV. EVALUATION PROTOCOL AND CONFIGURATION PLAN
   A. Other ETC Field Performance Evaluations ............ 15
   B. FDOT Evaluation Parameters ........................... 15
   C. FDOT Evaluation Plan .................................. 20

V. EVALUATION FINDINGS .................................... 21
   A. General Operation of ETC Systems .................... 21
   B. Operating Characteristics of Participants ............ 26
   C. General Test Plan for Electrical Field Measurements 31
   D. Summary of Evaluation Findings ....................... 33

VI. OTHER EVALUATION ISSUES ............................ 37
   A. Health and Performance Factors ....................... 37
   B. Recommendations for Further Evaluation ............. 43

VII. CONCLUSIONS ............................................ 43
GLOSSARY OF TERMS

**Active system** = utilizes a transponder which takes its power from the vehicle itself.

**Analog VES system** = never converts photo images to digital form, but stores image on video tape for manual extraction at a later time (i.e., no provision for automatic extraction of images).

**Anomalies** = something different, abnormal, peculiar, or not easily classified. For purposes of this evaluation, anomaly categories were classified as: (1) excluded (procedural/set-up problem, corrected problem, inconsistent conditions), (2) invalid transactions, (3) missing or bad photos, and (4) incorrect photos.

**ANSI** = American National Standards Institute.

**Antenna beam width** = generally interpreted as the 3dB beam width, or the space where power radiated from the antenna is within 3dB (or a factor of 0.5) of its maximum value.

**Anti-passback** = an evaluation typically performed during optional evaluations, where vehicles enter/leave the field of interrogation in the toll lane in short periods of time to determine the number of separate transactions that occur for a particular vehicle.

**ASK** = (amplitude shift keying) a modulation technique in which the carrier wave is keyed on and off by the binary data signal.

**AVI** = (automatic vehicle identification) transponder based systems which monitor passage of vehicles passed fixed sensors to capture such information as time, location, and unique identification data.

**Backscatter** = electromagnetic field reflected from objects in the field of view of a transmitting antenna.

**BCS** = block check sequence.

**Bit** = a unit of computer information, a binary digit, equivalent to the result of a choice between two alternatives (as “yes” or “no”, “on” or “off”), physically represented by an electrical pulse or magnetized spot. Sixteen bits equal 1 word.

**Bit (data transmission) rate** = the number of bits transmitted in a given second.

**Byte** = a group of adjacent binary digits (8 bits=1 byte) that a computer processes as a unit.

**CENTER** = (center frequency) the frequency at the center of the spectrum analyzer display or plot.

**Checksum** = a code at the end of a frame that tells exactly how many bytes were transmitted.
“Core Battery” evaluations = those evaluations, occurring on Tuesdays and Wednesdays, that were mandatory for all participants. A total of 1,214 separate vehicle passages constituted these evaluations, including evaluations of the VES subsystem.

CRC = (cyclic redundancy checking) an error control method which involves the addition of a block check sequence (BCS) of bits to the data message. The whole data stream (message plus BCS) should obtain a zero remainder if no error has occurred.

CW = continuous wave.

db-microvolt = (decibel) twenty times the logarithm of the signal voltage referenced to one microvolt. For example, A db-microvolts is equal to 20 Log (A (volts)/0.000001 volts).

Digital VES system = capable of immediately converting images into digital form for storage and/or retrieval.

Digitizing oscilloscope = an electronic instrument capable of displaying a digitized (or broken into discrete values) version of an input signal (y-axis) versus time (x-axis).

Director = a director is a half wavelength dipole which receives energy radiated from the antenna and then re-directs it in the desired direction.

DSR = digital shift register.

EMF = electro-magnetic fields.

EMI = electro-magnetic interference.

ETC = (electronic toll collection) advanced toll collection systems using transponders and telecommunications devices such as AVI. ETC provides for increased toll lane throughput with non-stop toll transactions in both read and read/write systems.

ETTM = (electronic toll and traffic management) expands on basic AVI or ETC by utilizing two-way communication between vehicles and roadside to provide a full range of traffic and fleet management, safety and incident management, and toll management functions.

FCC = Federal Communications Commission.

Frame = a time interval containing a complete single lane cycle.

Frame rate = the rate at which frames are repeated on a single lane.

FSK = (frequency shift keying) a digital modulation technique where the frequency is changed between two discrete values each generated by a separate oscillator embedded in the transponder.
GHz = (gigahertz) a measure of frequency (1 billion cycles per second).

"Handshakes" = a term used to describe the rate (and amount) of data transmission.

IEC = International Electrotechnical Commission.

Inductive loop antenna = an antenna constructed of a wire loop embedded in the pavement that couples energy via a time varying magnetic field passing through the loop.

Interrogator = the ETC antenna that first identifies or acknowledges a vehicle as it enters the toll plaza.

kbps = (kilobits per second) a measure of the speed of data flow (1,000 bits per second).

kHz = (kilohertz) a measure of frequency (1,000 cycles per second).

Land mobile service = a mobile service between base stations and land mobile stations, or between land mobile stations.

Land mobile station = a mobile station in the land mobile service capable of surface movement throughout the U.S.

Land station = a station in the mobile service not intended to be used while in motion.

Manchester encoding = an encoding technique in which a binary one is represented by a transition from a logic “one” to a logic “zero” at the center of each bit period, and binary zero is represented by an opposite transition.

MHz = (megahertz) a measure of frequency (1 million cycles per second).

Micro- = one millionth of a unit (i.e., 10^-6). 

Microstrip antenna = an antenna constructed of a patch of metal deposited on a dielectric slab.

Microwave = high frequency electromagnetic signal with a frequency between 300 MHz and 300 GHz (delimiting frequencies vary).

Milli- = one thousandth of a unit (i.e., 10^-3).

MKR = (marker) a diamond shape marker indicating a specific amplitude/frequency.

Modulation = the process of varying the wave amplitude, frequency, or phase of a transmission signal.

Nano- = one billionth of a unit (i.e., 10^-9).
Optional evaluations = non-mandatory portion of this evaluation, typically beginning no earlier than Wednesday night and lasting through Thursday. As an example, these evaluations included shadowing, anti-passback, transponder placement on trailers, multiple transponders in a single vehicle, etc.

Passive system = utilizes a transponder which takes its power exclusively from the radiating antenna field.

Patch array = an array constructed of microstrip antennas arranged in a two dimensional pattern.

Polarization = the particular state, either positive or negative, with reference to two poles or electrification. In ETC, this is defined as the action or process of affecting radiation so that the signal wave assumes a different form. In most cases, a defined polarization (orientation) of the transponder must be maintained to assure it will be detected.

Power density = a measure of the radiated field intensity in watts per squared centimeter, or the square of the electric field plane wave divided by the characteristic impedance of the medium.

Read/write = a type of ETC technology where two-way communication exists. The transponder is not only capable of reflecting unique pre-programmed data, but variable data in real-time can also be written, stored, and later extracted.

REF = amplitude reference level for spectrum analyzer display or plot.

RES BW = (resolution bandwidth) determines how well the analyzer can resolve, or separate, two or more closely spaced signal components.

RF = (radio frequency) a method of wireless communication which uses electromagnetic energy.

Semi-active system = utilizes a transponder which has a self-contained battery with an expected lifetime.

"Shadowing" = a type of optional evaluation where vehicles follow as close as possible to each other as they pass thru the toll plaza lane in order to determine if separate vehicles are detected.

“Smart card” = a contactless (no metal contacts ensuring longer wear and resistance to vibration), credit card size, card that uses a self-contained microprocessor and memory to store and process such items as toll/fare or banking transactions, driver identification data, and telephone information.

SPAN = the total width of the displayed spectrum.

SPAN 0Hz = a spectrum analyzer mode of operation in which the display is essentially a time domain representation of signal amplitude at a particular frequency.
**Spectrum analyzer** = a tool used in transmission signal analysis that can display peak signal frequency and amplitude variations on a logarithmic scale, and simultaneously measures voltages.

**SWP** = (sweep speed) the time at which the electron beam of the display sweeps the screen.

**TDMA** = (time division multiple access) a protocol that implies that sample values from several different lanes can be integrated into a single waveform.

**Transceiver** = a radio device that uses many of the same components for both transmission and reception.

**Transponder** ("tag") = a radio device that typically, upon receiving a designated signal, emits a radio signal of its own that is used for detection, identification, and location. Transponders can be passive, semi-active, or active.

"**Valid transaction**" = defined by CUTR according to a 4-part criteria. First, the correct vehicle in the correct sequence in the correct lane had to be acknowledged. Second, a beginning balance had to be "read" from the tag and a new balance had to be "written" to the tag in order to constitute the transaction. Third, the correct amount had to be debited during the transaction. Finally, if a known violator, a correct and legible license plate image had to be produced.

**VES** = violation enforcement system.

**Yagi antenna** = a type of antenna, named after Japanese Professor H. Yagi, that is constructed of a series of horizontal rods decreasing in length from front to back. (Also, a commonly used TV antenna).

**Zero span** = an operating mode of a spectrum analyzer that allows the amplitude of a single frequency to be examined over time.
I. EXECUTIVE SUMMARY

The purpose of this evaluation was to examine and document performance capabilities and operating characteristics (features) of electronic toll collection (ETC) technologies, and determine what ETC technologies are available for 1993 procurement. It was not the intention of this evaluation to determine the preferred vendor for procurement of an ETC system for the Florida Turnpike, or to eliminate any potential proposers for this future installation. Given the extremely short timeframe for evaluation (a total of 24 hours spread over three days with each participant), this evaluation does not serve as a statistically valid experiment, but should be utilized to advance the general knowledge base of ETC performance testing. It is also important to mention that new conventional toll collection equipment, expected to be installed by the Florida Turnpike over the next year, was not integrated with this evaluation.

Very little performance evaluation of the various ETC technologies has been formally documented, and for the most part that which exists is proprietary. (The majority of the perception toward ETC performance reliability, good or bad, is vendor-generated). Therefore, "standardized" guidelines were not available to follow. The Center for Urban Transportation Research (CUTR) developed an evaluation protocol and configuration plan that was simple, consistent for each participant (i.e., "core battery" evaluations), and as time permitted allowed for optional evaluations to explore known problem areas or substantiate claims of performance. This evaluation served to establish a relative basic performance indicator in terms of percent of "valid transactions", including integration of a violation enforcement subsystem (VES) component.

Five participant "teams" were evaluated between November 1992 and January 1993. These teams, in chronological order of evaluation, included:

- AT&T Smart Cards Systems with Mark IV-IVHS Division,
- Mark IV-IVHS Division,
- Amtech Systems Corporation,
- Applied Computer Science with Saab-Scania Combitech Traffic Systems, and

Two additional participants were scheduled to be evaluated during this evaluation period (Hughes Aircraft Company and AT/Comm, Inc.), but each had to take themselves out of the Florida Department of Transportation (FDOT) evaluation due to other priorities. An examination of these ETC technologies will be conducted in some fashion, but not included as part of evaluation documentation.

Under the environment of this evaluation process, and based on the examination of the five participant teams conducted by CUTR, several basic conclusions can be reached.

1. All participants were successfully able to demonstrate their basic operating characteristics in the field, that were indicated in writing prior to their respective field evaluations.

2. No participant could consistently transmit and receive signals when the transponder was mounted directly behind the metal oxide (Sungate) windshields.

3. Power density measurements indicated a range below the national standards for exposure levels.

4. Based on total "anomalies" (please see glossary), a general indicator of readiness...
and preparedness for the rigors of this evaluation, success rates ranged from a low of 70.8% to a high of 98.2%.

5. Based on “valid transactions” (please see glossary) only, the participants exhibited a success reliability in the range of 89.7% to 98.4%.

6. Based on “valid transactions”, without the VES component, the participants exhibited success reliability in the range of 90% to 100%. (The other participants ranged from 96.3% to 99.9%).

7. Integration of violation enforcement capabilities proved to be the biggest weakness for all the participants. CUTR believes this problem resulted primarily from inadequate integration between VES and ETC, not necessarily from inadequate VES technology. Even the most successful participant had almost 37% of their photo opportunities resulting in bad or missing photos. The other participants had between 44% and 68% of their photo opportunities resulting in missing or bad photos. (The most successful participant was the only participant that chose to incorporate a digital conversion process for its VES component).

8. Finally, given the brief examination of the ETC technologies in this evaluation process, it appears that acceptable performance reliability can be achieved. FDOT should continue to move cautiously forward on their ETC procurement schedule. Most importantly, adequate time (at least 45-60 days) should be reserved for final performance acceptance testing under a rigorous, controlled, integrated evaluation plan.

II. PURPOSE AND SCOPE

It is the purpose of this evaluation to examine and document the general performance capabilities and operating characteristics of ETC technologies. It is not the intention of this evaluation to determine the preferred vendor for procurement and installation of an ETC system for the Florida Turnpike, or to eliminate any potential proposers for this future installation.

The documentation of this evaluation expands on CUTR’s previous (qualitative only) evaluation of ETC technologies, and represents one of the first attempts to evaluate the performance of various ETC technologies conducted within a rigorously controlled time schedule under predetermined evaluation parameters.

Given the extremely short timeframe for evaluation (24 hours over three days with each participant), this evaluation does not serve as a statistically valid experiment, but will be utilized to advance the general knowledge base of ETC performance testing. Additionally, the evaluation findings will provide some assistance to FDOT in the development of a system-wide ETC technology performance specification.

The field evaluations have occurred over a three-month period (November 1992-January 1993), with the overall project constituting a twelve-month, research and documentation effort. It was CUTR’s goal to maximize the opportunity to capture field performance data under varying conditions during the three-month, field evaluation timeframe. New conventional toll collection equipment expected to be installed by the Florida Turnpike over the next year was not examined or integrated as part of this evaluation.
III. BACKGROUND

CUTR established a “core battery” of evaluation parameters such that all participants would be subjected to similar conditions. The areas of performance during field evaluation included: reliability (with and without violation enforcement), and the ability to demonstrate operating characteristics (i.e., signal power level, transmission frequency, and data transmission rate).

The following “core battery” of evaluation parameters were applied and assessed to the greatest extent possible during the field performance evaluation:

1. Varying vehicle speeds (5-mph increments, stop-n-go to 50 miles/hour). The Florida Highway Patrol assisted with high-speed (greater than 25 miles/hour).

2. Varying vehicle types (passenger cars, vans, light trucks, and heavy trucks), progression sequence, and gaps between vehicles. Higher speeds required larger gaps between vehicles for safety.

3. Varying degrees of windshield tinting (metal oxide) and angling.

4. Inclusion of a violation enforcement subsystem to be interfaced with the ETC system (processing license plate images during daylight, twilight, and nighttime periods).

CUTR solicited operating characteristics from each participant prior to the commencement of field evaluations. These range of stated operating characteristics, listed in Table 1, were confirmed to the greatest extent possible during the field performance evaluations.

The Sawgrass Expressway (two side-by-side lanes at the Sunrise mainline plaza), was selected by the FDOT Turnpike Office as the venue for the ETC field performance evaluations. This location is about 12 miles west of downtown Ft. Lauderdale, in Broward County, Florida.

FDOT took the lead role in initially contacting participants and establishing their respective commitment and liability for participation. CUTR coordinated with each participant regarding evaluation protocol, time periods of evaluation, plaza equipment installation and removal, maintenance-of-traffic, and installation of transponders.

FDOT published a “Letter of Interest” solicitation regarding the ETC field evaluations in the Florida Administrative Weekly, and several other national publications.

FDOT supplied a fleet of 10 vehicles and vehicle operators for this evaluation. The evaluation fleet consisted of the following vehicle types:

- 5 - passenger cars
- 2 - commercial vehicles (5-axle box trailer, 5-axle flat bed)
- 2 - vans (one with metal oxide windshield)
- 1 - pick-up truck

CUTR convened a pre-field performance evaluation scope meeting (September 30, 1992), mandatory for participants to attend, at the Sawgrass Expressway toll administration building (Deerfield Plaza). The purpose of this scoping meeting was to facilitate questions and answers, discuss the publication of findings,
review evaluation protocol and parameters, visit and inspect the evaluation site (Sunrise main-
line plaza), and conduct “lottery-style” drawing for participant evaluation schedule.

All costs associated with ETC equipment installation and removal was the responsibility
of the participants. Advance warning signage and channel-
ization devices were the responsibility of FDOT. CUTR repre-
sentatives were present at the evaluation site during all field performance evaluations.

During this time CUTR was responsible for monitoring per-
formance evaluations (i.e., obtaining a hard copy printout and license plate image (if ap-
plicable) from the participant immediately following each vehicle fleet passage), completing a performance test diary (a separate page for each vehicle configuration passage), and cataloging the field performance evaluations on video tape and 35mm color slides.

<table>
<thead>
<tr>
<th>Table 1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>System Operating Information</strong></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>DATA TRANSMISSION TECHNIQUE</th>
<th>RF, RF/MICROWAVE</th>
</tr>
</thead>
<tbody>
<tr>
<td>DATA TRANSMISSION FREQUENCY</td>
<td>READ: 134.2 kHz - 2.45 GHz</td>
</tr>
<tr>
<td></td>
<td>WRITE: 134.2 kHz - 2.45 GHz</td>
</tr>
<tr>
<td>TRIGGER/INTERROGATION TECHNIQUE</td>
<td>RF/MICROWAVE, RF @ 910 MHz</td>
</tr>
<tr>
<td></td>
<td>WITH 20 MICRO-SECOND</td>
</tr>
<tr>
<td></td>
<td>UNIMODULATED CARRIER PULSE</td>
</tr>
<tr>
<td></td>
<td>RF, DIRECT RF</td>
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<tr>
<td>TRIGGER/INTERROGATION FREQUENCY</td>
<td>134.2 kHz - 2.45 GHz</td>
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<td>APPROXIMATE SYSTEM RANGE</td>
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<td>MODULATION TYPE</td>
<td>UNIPOLAR ASK (MANCHESTER ENCODED), FSK, SINGLE-SIDE</td>
</tr>
<tr>
<td></td>
<td>BAND AM (CLOCKWISE AND</td>
</tr>
<tr>
<td></td>
<td>COUNTERCLOCKWISE POLARIZED), FM FSK</td>
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<tr>
<td>RF/MW COMMUNICATION BAND WIDTH</td>
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<td>DATA MESSAGE (CODE) TYPE</td>
<td>VARIABLE, BOTH FIXED AND</td>
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<td></td>
<td>VARIABLE WITH FLEXIBLE</td>
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<tr>
<td></td>
<td>PONTONING,</td>
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<td></td>
<td>COMMAND-DRIVEN LINK</td>
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<tr>
<td></td>
<td>(VARIABLE), FIXED</td>
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<tr>
<td>DATA MESSAGE LENGTH</td>
<td>64 BITS, 128 BITS (256 BITS IN 1993)</td>
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<tr>
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<td>WITH 3K BYTES STORAGE, 64 KBITS</td>
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<tr>
<td>DATA TRANSMISSION RATE (reader-to-tag) bps</td>
<td>READ: 9600 bps - 600 Kbps</td>
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<td>WRITE: 9600 bps - 500 Kbps</td>
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<tr>
<td>COMMUNICATION LINK RATE (reader-to-processor)</td>
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<td>0.110-39.4 kb, 38044 kb</td>
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<td>TRANSPONDER TYPE AND POWER SOURCE</td>
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<td>VEHICLE POWERED), TWO-WAY</td>
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<td>SEMI-ACTIVE RF WITH INTERNAL</td>
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<td>BACKSCATTER, SEMI-PASSIVE</td>
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<td>BACKSCATTER, PASSIVE</td>
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<tr>
<td>ANTENNA TYPE</td>
<td>OVERHEAD YAGI, IN-GROUND</td>
</tr>
<tr>
<td></td>
<td>COLLINEAR ARRAY, PATCH</td>
</tr>
<tr>
<td></td>
<td>ARRAY, LOOP SIDE-MOUNT OR</td>
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<td>LOOP IN-GROUND</td>
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<tr>
<td>RADIATED POWER-READER</td>
<td>0-100 MICROWATTS PER SQUARE</td>
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<td>RADIATED POWER-TRANSPONDER</td>
<td>0-100 MICRO WATTS PER SQUARE</td>
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<td>CENTIMETER</td>
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<tr>
<td>ANTENNA BEAMWIDTH (OR FIELD OF VIEW)</td>
<td>3 TO 5 METERS (30-60 DEGREES),</td>
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<td>12 FT. X 12 FT. X 12 FT. AREA</td>
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<td>READER POWER REQUIREMENTS</td>
<td>90-264 VOLTS AC, 40 WATTS,</td>
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<td></td>
<td>WITH 12 VOLT DC BATTERY</td>
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<tr>
<td></td>
<td>BACKUP</td>
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<tr>
<td>OTHER</td>
<td>CONTACTLESS SMART CARD</td>
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<tr>
<td></td>
<td>TECHNOLOGY,</td>
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<tr>
<td></td>
<td>COMMUNICATION INTERFACE:</td>
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<tr>
<td></td>
<td>RS 232C @ 9600 BAUD OR RS</td>
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<tr>
<td></td>
<td>422A @ 100K BAUD, BATTERY LIFE</td>
</tr>
<tr>
<td></td>
<td>GREATER THAN 5 YEARS</td>
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IV. EVALUATION PROTOCOL AND CONFIGURATION PLAN

A. Other ETC Performance Evaluations

Very little performance evaluation of the various ETC technologies has been formally documented. CUTR has investigated the extent to which performance evaluation and testing of ETC technologies has occurred (or is planned to occur). This investigation has served to obtain agency feedback and guidance in the FDOT evaluation.

Many of the toll collection agencies that have implemented or are investigating ETC systems have conducted some type of performance testing. However, much of this evaluation has been conducted under uncontrolled conditions. Unfortunately, the findings of these evaluations have not been formally documented and published, and in many cases the results are proprietary. Furthermore, test plans that are available indicate that these evaluations were not standardized tests and satisfy only specific agency concerns or requirements.

Clearly, there is a need to establish a nationally accepted, standardized testing procedure, such that all industry vendors could be “pre-qualified” in a consistent manner by an independent, unbiased, national standards agency. The results of these standardized tests should also be available to anyone who requests them. Table 2 summarizes the general status of ETC performance evaluations.

B. FDOT Evaluation Parameters

Evaluation Periods and Participants

The Tuesday-Wednesday-Thursday dates available for the five field performance evaluation participants were drawn in “lottery-style” fashion as follows:

1. AT&T Smart Cards Systems and Solutions (Bridgewater, NJ)/Mark IV-IVHS Division (Ontario, Canada) - November 17-19, 1992.


3. Amtech Systems Corporation (Dallas, Texas) - December 8-10, 1992.


5. Kiewit (MFS) Network technologies (Omaha, Nebraska)/Texas Instruments (Dallas, Texas)/Saab-Scania Combitech Traffic Systems (Sweden and United Kingdom) - January 19-21, 1993.

Two additional participants (Hughes Aircraft Company and AT/Comm, Inc.) responded to FDOT’s solicitation, attended the September 30, 1992, scoping meeting, and were scheduled for evaluation. Unfortunately, these two participant teams eventually had to drop out of their scheduled evaluations.

It was the intention of this schedule to also afford participants the opportunity to install and pre-test their equipment no more than two days prior to their respective evaluation dates, and remove their equipment within two days following their respective evaluation dates. This strict and rigorous schedule was administered to each participant to basically observe their ability to perform under time-pressure conditions.
<table>
<thead>
<tr>
<th>AGENCY</th>
<th>STATUS</th>
</tr>
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</table>
| New Hampshire Bureau of Turnpikes | • Have tested AT/Comm  
• No results were published  
• No reports available  
• Started testing Dec. 16, 1991 - 100 vehicles, 2 lanes (side-by-side)  
• Completed Dec. 1991 testing within 4 weeks  
• Need better control (reconciliation of reports) and more coordination with vehicles  
• About to commence a new round of testing of several vendors' equipment |
| E-Z Pass Group:  
• Penn. Turnpike Commission  
• NJ Highway Authority (Garden State Parkway)  
• Port Authority of NY/NJ  
• NY State Thruway  
• Triborough Bridge & Tunnel Authority  
• NJ Turnpike  
• NY Bridge Authority | Pennsylvania Turnpike Commission:  
• Tested Eureka and Mark IV for 6 months  
• Did not publish findings  
• Had speed problems reading transponders (less than 3 mph)  
New Jersey Highway Authority (Garden State Parkway):  
• Testing AT&T/Mark IV and Amtech  
• Not releasing any information at this time  
Port Authority of New York and New Jersey:  
• Have tested Amtech (read only) for buses at JFK Airport  
• Tested Amtech and AT&T/Mark IV in Fall 92 for 8 weeks, these tests extended to February 1993, results are still forthcoming  
• Currently there are no available test plans  
• Stated that the NY State Thruway has the most detailed test plans  
• Lincoln Tunnel has ETC for buses only  
New York State Thruway:  
• Tested at Spring Valley NY which resulted in two vendors being selected: Amtech and AT&T/Mark IV  
Triborough Bridge and Tunnel Authority:  
• Have developed Request for Proposals for the "Procurement of Compatible Electronic Toll Collection Equipment for various Participating Agencies"  
• Test protocols (plans) are available  
• Have tested Amtech (read only) at Verrazano-Narrows Bridge |
| Illinois State Toll Highway Authority | • Tested Eureka and X-Cyte  
• RFP for the "Design, Installation and Testing of a Pilot AVI Toll Collection System" is available  
• Performance test notes and results are available  
• Selected AT/Comm, prototype test scheduled for March-April 1993 |
| Orlando-Orange County Expressway Authority | • Was to have conducted a 60-day acceptance test of Mark IV in November 1992  
• Installation originally planned for Sept. 1992 (17-18 lanes) is delayed |
<table>
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| Virginia DOT (Dulles Fastoll Project) | • Tested Amtech - 1991  
• Tested Mark IV, Kiewit - Texas Instruments - 1992  
• Selected Kiewit (MFS) Network Technologies and will use the TIRIS-I equipment (formal award not yet made)  
• Test plans or results are not available |
| Castle Rock Consultants (HELP Crescent Program) | • HELP/AVI final report is available (very informative) |
| Caltrans (planned private, public/private toll roads) | • Provided "Compatibility Specifications for Automatic Vehicle Identification Equipment"  
• Published an RFP to implement electronic toll collection on Caltrans bridges, and issued AVI compatibility specification in March 1993 as part of a statewide toll system procurement  
• Lawrence Livermore National Laboratories have developed a prototype AVI system specification for Caltrans which uses micro wave backscatter technology |
| Oklahoma Turnpike Authority | • Test & monitor their system for reliability |
| Texas Turnpike Authority | • Have not done any performance testing, since the Amtech system they use is a vendor owned and operated as demo project  
• Recently decided to keep Amtech for next few years |
| Harris County (Houston) Tollway Authority - (Sam Houston Tollway) (Hardy Tollway) | • Have an Amtech system (prime is Cubic)  
• Installation completed and operation began in late October 1992 at both toll facilities |
| International Bridge, Tunnel, and Turnpike Association (IBTTA) | • No information on performance testing is available |
| Ontario Ministry of Transportation | • Had planned to do testing, but it was canceled  
• Planning to test read/write technology with connection to a smart card at a later date |
| Florida DOT (Turnpike Office) | • Five participant teams took part in controlled field performance evaluations (November 92 - January 93)  
• Only read/write technology was evaluated  
• Violation enforcement subsystem also was evaluated  
• Findings will assist in developing system wide performance specifications  
• RFP for procurement and installation expected to be advertised Nov. 1993 |
| Transport Canada | • Not doing any testing, but they are looking at the technology used in the HELP project (Mark IV)  
• They want to have an integrated system with about 38 different applications |
| Office of the Deputy Assistant Secretary of Defense | • They are investigating RF read/write technology for:  
(1) Asset Location  
(2) Data Transfer  
• Currently working on AVI system standard |
Participant Requirements

1. Two lanes of "read-write" ETC equipment were installed by participant in the toll plaza lanes. Power source hook-ups and conduit runs were reviewed at the September 30 project scoping meeting. These two lanes (Lanes 1 and 2, closest to the evaluation work trailer and plaza administration building) were utilized exclusively for ETC field performance evaluations.

2. A reader terminal was required of the participant to provide hard copy print-outs of transponder ("tag") identification number and account information (balance before and balance after) for each vehicle immediately following the completion of each separate vehicle fleet configuration passage.

3. A violation enforcement subsystem, with the ability to produce daytime, twilight, and nighttime hard copy photos of evaluation fleet vehicles' license plates, was required of the participant.

4. At least 15 transponders (at least 2 with purposely overdrawn or invalid accounts in order to "trigger" VES) were supplied and installed by each participant between 7 a.m. and 9 a.m. on the Tuesday morning of each evaluation period. Participants were also required to provide CUTR the unique transponder identification numbers and account information (initial balance) for each fleet vehicle.

Dissemination of Field Performance Evaluation Findings

One copy of the participant's own detailed field performance evaluations were provided to each participant team leader in May 1993.

Evaluation documentation was not finalized until all participants had completed their participation. The confidentiality of each participant will be maintained in all published reports. Any materials that relate to methods of manufacture or production, potential trade secrets, potentially patentable material, actual trade secrets, business transactions, or proprietary information received, generated, ascertained, or discovered during the course of the ETC field performance evaluations shall be confidential.

Evaluation Configuration Plan Assumptions

1. An average of seven minutes/evaluation run, or about eight evaluation runs/hour (includes turnaround and re-queuing of vehicle fleet).

2. As a minimum, 1,214 separate vehicle passes (i.e., "core" battery evaluation) occurred over the 24-hour evaluation period, plus "optional" runs as time permitted. In total, 65 different fleet vehicle configurations were examined, and each configuration was run twice.

3. Configurations varied by vehicle sequence, vehicle speed, and single-lane vs. dual-lane reconciliation.

4. Six vehicle sequences (A-F) for single-lane reconciliation were utilized as shown below such that each vehicle type followed each other vehicle type as they passed through the toll plaza.

   A = car, WB40, car, van, pick-up truck, van, car, car, WB40, car
   B = car, car, car, pick-up truck, van, van, WB40, WB40, car, car
C = car, WB40, car, pick-up truck, car, van, van, WB40, car, car

D = car, van, car, WB40, pick-up truck, car, WB40, van, car, car

E = car, car, van, pick-up truck, WB40, van, car, WB40, car, car

F = Florida Highway Patrol car (speeds greater than 25 mph only)

5. Ten vehicle sequences (G-P), grouped in pairs of five as shown below, for dual-lane reconciliation were utilized such that each vehicle type was side-to-side with each other vehicle type as they passed through the toll plaza.

G (14-foot lane) = car, car, WB40, car, WB40
H (12-foot lane) = van, car, van, car, pick-up truck
I (14-foot lane) = WB40, van, WB40, car, car
J (12-foot lane) = van, car, car, pick-up truck, car
K (14-foot lane) = car, WB40, van, WB40, car
L (12-foot lane) = car, van, pick-up truck, car, car
M (14-foot lane) = van, WB40, pick-up truck, WB40, car
N (12-foot lane) = car, van, car, car, car
O (14-foot lane) = van, car, WB40, car, WB40
P (12-foot lane) = van, car, car, car, pick-up truck

6. Eleven vehicle fleet speeds (A-K) for reconciliation were utilized, as shown below, in 5-mile/hour increments beginning with stop-and-go (A) to 50 miles/hour (K).

A = stop & go (2.5mph avg.)
B = 5mph
C = 10mph
D = 15mph
E = 20mph
F = 25mph
G = 30mph
H = 35mph
I = 40mph
J = 45mph
K = 50mph

7. Evaluations commenced no earlier than 9 a.m. and ended no later than 5 p.m. (except on Wednesdays which were reserved for nighttime photographic surveillance/enforcement evaluations) to avoid the morning and evening peak-hour traffic. Evaluations were conducted in the non-peak (northbound) traffic direction.

8. Typically, one break during the day (Tuesdays and Thursdays) occurred during lunch at 1 p.m. - 2 p.m. On Wednesdays, two breaks occurred during lunch at 12 p.m. - 1:30 p.m., and dinner from 5:30 p.m. - 7 p.m. Typically, nighttime evaluations on Wednesdays began about 7 p.m. and continued until 10 p.m. If evaluations were on schedule, this left about 1.5 hours to begin optional evaluations on Wednesday night.

9. For safety purposes, vehicle fleet speeds of 30 mph-50 mph were run for vehicle sequence "F" only. This sequence was typically run just before the dinner break on Wednesdays. Four passes were made for 45 mph (two with violation enforcement activated), and four passes were made for 50 mph (two with violation enforcement
activated). This configuration (6g-6k) was always conducted with a single Florida Highway patrol car.

10. Evaluation of the VES was incorporated following the Wednesday lunch break through the end of Wednesday night.

11. Typically, Thursday was reserved for optional evaluations (i.e., shadowing, cross--lane reads, transponders on trailers, anti-passback, etc.), participant showcasing, or re-runs of “core battery” evaluations that could not be completed.

Evaluation Configurations

Table 3 illustrates the 65 different fleet vehicle configurations that were utilized in the “core battery” evaluations for each participant. Each configuration was run twice.

C. FDOT Evaluation Plan

Based on discussions with consultants and agencies who had previously attempted to obtain “handshakes” and data rate verification, one aspect in obtaining these measurements was found to be mandatory: reliance on direct vendor participation and assistance. Having the operating specifications from each participant alone did not ensure that these measurements could be made, especially considering the relatively short time this particular evaluation spent with each participant. There are too many variables outside of evaluator control, such as the specific data encoding and transmission scheme for each participant, to permit successful field verification and measurement.

Therefore, it was concluded that the electrical measurement technique could not be “standardized”. Furthermore, depending on the specific participant modulation and encoding scheme it could also be impossible to take a measurement of data rate transmission or “handshakes” without tapping into an intermediate frequency (or data output) signal from the interrogator. It was imperative, therefore, that CUTR had direct assistance from the participant to efficiently monitor transmission signals over time in order to separate carrier signal and background from actual data transmission.

Given the timeframe and participant evaluation schedules for this evaluation, it was recommended that the following protocol be introduced in order to provide for the highest probability of successful and accurate field measurements.

1. A standardized system information table was completed by each participant and transmitted to CUTR no later than at least one week prior to their evaluation period (summarized previously in Table 1).

2. The presence of a technology/operations “expert” was required from each participant to assist CUTR in field measurements and interpretation (this requirement later proved to be critical).

3. The participant was required to demonstrate that read/write occurrences were taking place, and the rate of read/write transmissions and the number of “handshakes” per vehicle passage. In order to conduct this demonstration it was necessary for the participant to also bring their own field equipment for the evaluation period, such as a digitizing oscilloscope and a means by which to get hardcopy of screen. It was the responsibility of each participant to assist CUTR by suggesting how best to verify this demonstration, and provide a hardcopy printout for each configuration run.
4. The data to be “read” from the transponder was the beginning account balance upon entering the toll plaza for each configuration run. The data to be “written” to the transponder was the account balance following each toll transaction. The actual real-time for each read/write occurrence was also recorded as part of the hardcopy printout. This time reference was synchronized and cross-checked with the video timer as CUTR video documented each evaluation.

5. At least one transponder was affixed to each vehicle. For evaluation fleet vehicles with metal-oxide windshields, at least one of the transponders was to be affixed behind the metal-oxide windshield. (By choosing to install an exterior transponder or an interior transponder in a location not directly behind the metal oxide windshield on the vehicles with the metal-oxide windshields, the participant was admitting his inability to successfully avoid signal attenuation).

V. EVALUATION FINDINGS

A. General Operation of ETC Systems

Introduction

The advent of low cost, custom integrated circuits (CICs) has introduced the possibility of allowing not only two-way communication but also on-board processing and driver interaction during the ETC process. It now appears possible for toll information to be stored on the vehicle and processed in a variety of ways. For example, there could be different accounts (representing different toll authorities) with different rates and other information on one tag. Current ETC systems generally take advantage of two-way (read/write) technology and on-board processing.

This section of the report gives an overview of the ETC technologies evaluated, and the operating principles upon which those technologies are based. The various components of a typical ETC system are identified, and the general operation of an ETC system are discussed by examining a typical two-way communication sequence (transaction). Finally, the different features afforded by the unique operating principles of the various ETC systems are outlined.

System Requirements

The general requirements for an ETC system are to provide a means of automatically charging a toll to a vehicle passing through a toll booth without the vehicle needing to stop. The system must be extremely reliable (at least as reliable as conventional toll collection equipment, given trade-offs in throughput, cost, etc.), under all weather conditions, and it must be immune to varying Electro-Magnetic Interference (EMI) in the local environment. For purposes of this evaluation, the system must have the ability to store the toll information and other data on the transponder (“tag”) and modify that information as the vehicle passes through the toll plaza (i.e., it must have read/write capability).

Specifically, the system must be resistant to:

- Interference from transactions being conducted on adjacent lanes (cross-lane reads)
- Signal transmission reflections from the plaza structure and other metal objects.
- Nearby EMI sources (pager’s, cellular telephones, etc.)
- Intentional efforts to compromise the system through:
  -- counterfeit tags
  -- illegally adding money to the tag
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The ETC system might also provide some means of automatic enforcement of toll violations. In accordance with recently passed state of Florida legislation, the system will be capable of taking a photograph of the license plate of any vehicle that has a bad tag, a tag with zero balance, or no tag at all, and send the warning or ticket to the vehicle owner.

Finally, the system must be easily interfaced with existing equipment, automatically provide for malfunctioning equipment (redundancy), and provide for the easy management and retrieval of the database generated by the system. Anti-fraud protection is particularly important. While it is highly improbable that someone could steal and manufacture the circuit design for the custom integrated circuit of a particular tag, as the equipment for manufacture is not commonplace, it is conceivable that someone could break the code for the tag and illegally program it.

**Parts of a System/Typical Transaction Sequence**

The components of an ETC system are listed below and illustrated in Figure 1.

- Transponder/tag
- Plaza computer
- Antenna/RF module
- Reader
- Violation enforcement system
- Lane controller (optional, but desired in Florida)

Different vendors may combine the various functions performed by these parts into a single device but all of these parts are present.

**Transponder/Tag**

The tag is the vehicle-mounted device that receives signals from the toll plaza, demodulates those signals into information that can be processed and stored on the tag and transmits information back to the toll plaza. There are several types of tags that correspond to the types of communication that take place between the toll plaza and the vehicle. The definitions that are discussed could more precisely be called conventions, as the status of ETC transponder technology is currently in a state of flux. The different types are: passive, semi-active, and active. Passive refers to a system based around a transponder that has no power source. In this case, the transponder simply reflects the signal back to the antenna. A semi-passive transponder reflects the signal also but has more sophisticated on-board processing of data. A semi-active transponder does not reflect but actually transmits its own signal using stored energy in a self-contained battery. The term "semi" refers to the fact that it requires a prompting signal to begin its operation. An active transponder transmits its own signal, and generally derives its power from the vehicle.

The relatively rapid evolution of ETC transponders has progressed from a Type I transponder that can only be "read" (or simply reflect a unique vehicle identification when interrogated), to a Type II transponder that can be "read" from as well as "written" back to in order to store and update unique variable data contained within the transponder such as entry/exit locations, account balance, vehicle maintenance and inspection reports, etc. Type III transponders are also available, which perform as Type II, and also have the capability to interact and communicate with the driver. Costs generally increase from a Type I to a Type III transponder.
Figure 1
Typical Components of an ETC System

Lane Controller
The function of the lane controller is to integrate all the activity that occurs in a toll lane. The extent of responsibility that the lane controller assumes varies from vendor to vendor. However, the minimum function in all the different systems is to send the toll transaction information in its final form to the host/plaza computer, and to effectively trigger the violation enforcement system. For some systems, the lane controller also takes on some of the responsibility of the data processing from the reader.

Antenna/RF Module
The roadside antenna comes in many forms depending on the choice of the vendor. For low frequencies (e.g., 130 kHz) the antenna is an inductive loop embedded in the road pavement. Most higher frequency (microwave) systems utilize overhead or side-mounted antennas. The RF module contains the circuitry required to modulate a microwave signal with the digital data to be sent to the tag (transmit), and de-modulate the microwave signal received from the tag (receive).

Reader
The reader takes the demodulated signal from the antenna/RF module and converts the digital signal into a form readable by the host computer.

Plaza Computer
The plaza computer is the final processing stage for all the data generated by system. It takes the toll information from the readers from each lane, the picture from the VES, and acts as an information manager. The toll plaza functions required for this system are to identify the tag, process the information stored on the tag, write back to the tag, and control all the other functions of the toll plaza. There will usually be one host computer for the entire system, one plaza computer for one or several toll plazas, and one lane controller and reader for each lane. How the different functions are divided between the three parts varies from vendor to vendor, but together they will perform the same general functions.
Violation Enforcement System

The VES consists of an interface to the lane controller, a camera for each lane, a triggering system to ensure that the picture is taken when the transponder is in the center of the vehicle, and a storage media for the pictures.

The primary differences between the different VES systems are in what form the images are stored and at what point the images are converted into different forms. The digitizing camera immediately converts the image into digital form for storage on a floppy drive. The analogue/digital system uses an analogue camera for each lane and a single digitizer or “frame grabber” for conversion into digital form. The all-analogue version never converts the images to digital form but stores the image on a video tape for later extraction by a toll plaza employee. There is no provision for automatic extraction of the license plate photograph under the all-analogue system.

The timing between the detection of the end of a vehicle and the taking of the pictures is very critical for the legibility of the license plate image. Vehicle presence and vehicle separation also are important elements in accurate and reliable picture taking. Lighting in the toll plaza may vary from plaza to plaza, and this may also affect the ability to produce legible license plate images. Normally, the lighting level in the area under the plaza canopy should be 25-foot candles. The Sunrise mainline plaza canopy was over 20 feet high (atypical), and thus specific adjustment in background lighting for this evaluation made by each participant was considered to be atypical.

B. Operating Characteristics of Participants

The following is a description of the five ETC system operations as observed by CUTR/USF from November 17-18, 1992 to January 19-21, 1993.

System 1 - Overview

This system was an active read/write system. The transponder is either windshield-mounted internally or front-bumper-mounted externally, and is capable of two-way communication. As the vehicle passes the reader site, it enters the field of view of an activation antenna. The antenna transmits a 20 micro-second activation signal (trigger) to the transponder, causing it to respond with its ID message. Since the system functions in a two-way communication mode, coded data are not only passed from the vehicle to the roadside unit, but data flow also occurs in the reverse direction, with a coded data message transmitted from the same antenna which functions as the transaction cycle antenna. The transponder stores both fixed code messages and variable code messages. In the two-way communication mode, first fixed codes are passed from the vehicle to the roadside, then variable messages (e.g., account balance and debit) are passed between the roadside and the vehicle.

The system uses either an overhead Yagi or a slot (in-pavement) antenna for sending and receiving RF signals. The overhead antenna is used to communicate with an internally-mounted transponder while the in-pavement antenna is preferable when an externally-mounted transponder is used. Figure 2 illustrates the test configuration for this system.

In order to represent the transponder’s data message on the transmitted RF signal, this system utilizes unipolar amplitude shift keying (ASK) modulation. This system used cyclic redundancy checking (CRC) to detect errors in the messages. CRC involves addition of a block check sequence (BCS) of bits to the data
message to be transmitted. The RF module performs a logical division of the whole data stream (message plus BCS) and should obtain a zero remainder if no error has occurred. Since the central unit covers multiple lanes, a time division multiple access (TDMA) protocol is used. In TDMA, values from several different lanes are integrated into a single time waveform.

**System 2 - Overview**

This system was an active read/write system. The cardreader (which a “smart card” is inserted) is a dashboard-mounted or windshield-mounted unit. The contactless card contains both a microprocessor as well as 3k bytes memory. The card stores both fixed code messages and variable code messages. The fixed code messages allow vehicle identification data (serial number) to be encoded on the transponder prior to its installation on the vehicle. Once encoded, the data message on the transponder is permanent. The variable code data, such as account balance, can be updated during the write cycle, as the vehicle goes through the toll plaza.

As the vehicle passes the reader site, the following sequence occurs. It first enters the field of view of an overhead Yagi “activation” antenna. The antenna transmits a 20 micro-second activation signal (trigger) to the transponder, causing it to respond with its ID message. Since the system functions in a two-way communication mode, coded data are not only passed from the vehicle to the roadside unit, but data flow also occurs in the reverse direction, with a coded data message transmitted from a second overhead Yagi “transaction” antenna. Figure 3 illustrates the test configuration for this system. In the two-way communication mode, first fixed codes are passed from the vehicle to the roadside, then variable messages are passed between the roadside and the vehicle. The system uses overhead Yagi antennas, primarily in order to avoid problems associated with a beam passing into adjacent lanes. By limiting the overhead antenna beam width to the lane width, cross-lane interference is minimized, allowing the system to operate in a multiple-lane environment.

In order to represent the transponder’s data message on the transmitted RF carrier signal, the system utilizes the digital modulation
System 3 - Overview

This system was an active read/write system. The transponder is a windshield-mounted or exterior unit containing a conditioning circuit, clock oscillator, memory, microstrip antenna and an internal lithium battery. The battery, which has a lifetime of approximately five years, classifies this system as a semi-active system. The transponder stores both fixed code messages and variable code messages.

As a vehicle enters the toll plaza, the following sequence occurs. It first enters into the field of view of an inductive loop antenna. The inductive loop antenna has a low frequency (100-120 kHz) signal running through it. Any vehicle (with or without a transponder) passing over the antenna, will disturb the antenna magnetic field, causing an RF microwave signal to be turned on and transmitted through a second overhead “boxed” antenna. The overhead “boxed” antenna will transmit a continuous wave (CW) signal. At this point, if the vehicle has a valid tag, the tag will modulate the reflected CW signal (backscatter), modify a portion of the signal and reflect it back to the antenna. The reflected signal carries the transponder identification code. Figure 4 illustrates the test configuration for this system.

The transponder contains a battery which keeps it continuously scrolling its content. There is a single bit that will flip itself when there is
changed between two discrete values. Each frequency is generated by a separate oscillator embedded in the transponder. Also with the FSK modulation technique, the logic levels are represented by successive pulses.

This system used CRC to detect errors in the messages. CRC involves addition of a block check sequence (BCS) of bits to the data message to be transmitted. The reader unit performs a logical division of the whole data stream (message plus BCS) and should obtain a zero remainder if no error has occurred.

Since the plaza computer covers multiple lanes, a TDMA protocol is used. TDMA implies that sample values from several different lanes can be integrated into a single waveform. The time interval containing a complete, single-lane cycle is called a frame. Each transponder message contains two frames; one of fixed data and the second of variable data.

**System 4 - Overview**

This system was an inductive, low frequency, system utilizing a passive transponder. The demonstrated equipment was operational only under the read mode. The transponder was an internally or externally mounted unit (an external tag was utilized in the "core" battery evaluations) containing a small ferrite antenna,
The low operating frequency and inductive loop antennas classifies this system as an inductive system. Due to the low frequency, the communication method used is "direct broadcast", which is very similar to two transceivers or a "walkie-talkie". As soon as the lane controller transmits, the information is received by the vehicle transponder, and there is no need to set up any communication protocol with the system. Data flow occurs only from the vehicle to the loop antenna; therefore, this was a one-way communication system.

System 5 - Overview

This system was a semi-active read/write system. This system was capable of addressing specific address fields in the transponder much as a microprocessor would access memory. The RF module/antenna was placed on the left-hand side of the toll lane at a height of 10 feet above the roadway. Figure 6 illustrates the test configuration for this system.

The two central features which describe this system are based on the concepts of circular polarization and the concept of memory addressing. Different polarization directions are used for different portions of the transaction, clockwise is used for reader to transponder communication and counter-clockwise is used for
transponder to reader communication. The transponder and reader are both designed to exploit this concept by being tuned to the different types of polarization. The use of switched polarization reduces the probability of interference from sporadic reflection.

The concept of memory addressing is borrowed from microprocessor practice. Whereas most other systems transfer the entire contents of the tag at one time (data frame), this system can access any given portion of the tag’s memory at a time. In addition, it is possible to vary the number of bits that are read before a checksum is conducted. The reader/lane controller can then treat the tag as just another memory address. If the reader determines that there is difficulty in conducting a successful transaction, it can decrease the number of data bits before it conducts a checksum, thereby increasing its reliability. These features also give the ability to encrypt the message just by using the capacity of the system. If the data location, data length, checksum length, and CRC check, are not what they should be the reader will know this is a bad tag.

The transponder for this system is a semi-active type requiring a start-up procedure before it can begin communicating. The RF module/antenna is a single unit device that modulates the Manchester encoded digital signal, from the reader, onto a microwave signal for transmission. The polarization of the outgoing waveform is rotated for transmission to the transponder.

This system demonstration decided to integrate the RF module with the antenna to boost the range between the antenna and the lane controller/reader. By performing demodulation at the antenna, only a low frequency data cable is needed between the antenna and the reader, in contrast to a length sensitive RF cable.

C. General Test Plan for Electrical Field Measurements

Electrical Test Procedure

All the electrical testing on the participating electronic toll collection systems were conducted in a static, controlled, environment. A static environment as used here implies that any vehicles used during the measurement process were stationary, and not moving through
the toll plaza. Table 4 lists the test equipment used by CUTFUS F to obtain the electrical field measurements.

**Table 4**

<table>
<thead>
<tr>
<th>EQUIPMENT ITEM</th>
<th>MAKE AND MODEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectrum Analyzer</td>
<td>Hewlett Packard-HP8592D</td>
</tr>
<tr>
<td>Radiation Monitor</td>
<td>Narda-Nar3616</td>
</tr>
<tr>
<td>Plotter</td>
<td>Hewlett Packard-HP7440A</td>
</tr>
<tr>
<td>Antenna Kit</td>
<td>A.H. Systems-AK18G</td>
</tr>
<tr>
<td>Oscilloscope</td>
<td>Gould-200 Mhz (DSO)4094</td>
</tr>
</tbody>
</table>

1. Signal Level Detection--Signal level detection was carried out using an RF hazard (radiation) monitor. If the monitor sensitivity was not high enough to properly detect the power density levels (which was the case for all the participants), a spectrum analyzer in conjunction with a calibrated antenna was used.

2. Frequency Allocation Verification--The participant's transmission (or carrier) frequency presence in the FCC allowable bands' was verified using a spectrum analyzer.

3. Frame Rate and Bit Rate Verification--Frame rate as well as bit rate verification were carried out using a digitizing oscilloscope. By connecting the oscilloscope to the participant's RF transmission module and running the system (in some cases using vendor-supplied “diagnostic software”), both frame and bit rates were witnessed and verified to the extent possible.

**Spectrum Analyzer Plots**

A spectrum analyzer is one of the most powerful tools available in signal analysis. The analyzer's graphic representation has two axes, frequency and amplitude. One of the most desirable features of a spectrum analyzer is its ability to simultaneously measure voltages which differ by a factor of 100,000 or more. The wide range is displayed by using the decibel, or dB, which is equal to 20 times the logarithm of the ratio of one voltage to another, or ten times the logarithm of the ratio of two powers. If one voltage is twice the other it is six decibels (+6dB) greater (if it were half, it would be -6dB). At 10dB per division it is possible to display 100dB if the graticule has 10 divisions, this represents a voltage range of 100,000 to 1. By selecting the reference unit to dB-microvolt, the signals are represented with respect to 1 microvolt. Unlike a linear scale, where each increment represents a fixed difference between signal levels, each increment on a logarithmic scale represents a fixed ratio between signal levels.

Another extremely useful feature of a spectrum analyzer is the ability to display input signals

---

* Five particular frequency bands within the microwave region are permitted by the Federal Communication Commission (FCC) for AVI systems. These are 915 (+ or - 13) MHz, 2450 (+ or - 15) MHz, 5800 (+ or - 15) MHz, 10525 (+ or - 25) MHz, and 24125 (+ or - 50) MHz.
versus frequency, and to accurately measure the peak signal frequencies. Through the use of markers, peaks can easily be identified and a numeric representation of the peak signal's frequency as well as amplitude is achieved. This feature was used extensively in obtaining the frequency and maximum power level measurements described herein. Yet another feature of a spectrum analyzer is the ability to display amplitude variations of a single frequency signal versus time. By centering on a single carrier frequency and selecting “zero span”, the analyzer in this mode can be, in some cases, be used to help ascertain the frame rate of a particular lane’s TDMA signal.

D. Summary of Evaluation Findings

Statistical Performance Comparisons

The ETC “core battery” field performance evaluations included runs at different speeds with different orderings of the vehicles (configurations). Neither the speed nor the configurations appeared to have any influence in the occurrence of invalid transactions or in the occurrence of missing/bad photos. Figure 7 illustrates the percent of invalid transactions, both including and excluding violation enforcement criteria, for the participants.

The number of photo opportunities was different for each participant since it depended on the number of invalid transponders supplied by the participant. Figure 8 illustrates the percent of missing or bad photos for each participant.

Electrical Measurements

Based on the electrical measurements made, several general conclusions can be drawn. Table 5 gives a summary of the electrical verification measurements made by CUTR/USF as part of the field performance evaluations.

As mentioned previously, the carrier frequency is an important parameter for an ETC system. Five FCC allowable bands have been identified for AVI/ETC operation as follows: 915 (+ or - 15) MHz, 2450 (+ or - 15) MHz, 5000 (+ or - 15) MHz, 10,525 (+ or - 25) MHz, and 24,125 (+ or - 50) MHz. The participants, with one exception, used carrier frequencies falling within the first two FCC allowed bands. The
Figure 8
Percent of Missing or Bad Photos By Participant

![Bar chart showing percent of total violator photo opportunities by participant.]

Table 5
Summary of Electrical Measurement Results

<table>
<thead>
<tr>
<th>OBSERVATIONS</th>
<th>System 1</th>
<th>System 2</th>
<th>System 3</th>
<th>System 4</th>
<th>System 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier Frequencies (MHz)</td>
<td>920.6</td>
<td>920-921.4</td>
<td>903-911</td>
<td>0.1342</td>
<td>2.428</td>
</tr>
<tr>
<td>Estimated Peak Power</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(microWatts/Sq. cm. @ distance)</td>
<td>0.0494 @ 3.5 meters</td>
<td>0.062 @ 3.5 meters</td>
<td>1.552 @ 3.5 meters</td>
<td>0.0475 @ 0.01 meters</td>
<td>0.0056 @ 1 meter</td>
</tr>
<tr>
<td>Frame Rate (micro-seconds)</td>
<td>0.825</td>
<td>1.2</td>
<td>13.3</td>
<td>300</td>
<td>n/a</td>
</tr>
<tr>
<td>Bit Rate (kbps)</td>
<td>500</td>
<td>500</td>
<td>9.6</td>
<td>8.0</td>
<td>66.7</td>
</tr>
</tbody>
</table>
one exception is the TI (Tiris I) system whose 134 kHz signals were well below the FCC allocations for microwave AVI systems.

Beyond FCC compliance, other factors to consider with regard to carrier frequency choice are susceptibility to interference, and bit rate limitations. As illustrated in the spectrum analyzer plot in Figure 9, local interference was present in the Sunrise Toll Plaza’s electromagnetic environment at around 930 MHz, which was close enough in frequency to cause some problems for participants operating in the 915 (+ or - 15) MHz FCC allowed band. In contrast, as seen in Figure 10, no such local interference signals appeared to be present around the 2450 (+ or - 15) MHz band. Although the situation may change in the future, the 900-1000 MHz frequency range has become very crowded with increased use of cellular telephones, pagers, utility meter readers, etc., operating in this range. In fairness, participants were able to overcome the 930 MHz interference signals and obtain ETC read/write results with their systems. It should also be mentioned that 2450 MHz is also the frequency used in most microwave ovens.

Bit rate limitation imposed by frequency choice is primarily an issue with the inductive loop systems due to the low frequency used. Without entering a detailed discussion of modulation techniques, the maximum bit rate is a fraction of the carrier frequency, thus an inductive loop system, for example, simply is not capable of 500 kbps bit rates handled quite easily by higher frequency carrier schemes.

In regard to the peak power measurement, it should be emphasized that the listed numbers are considered a “rough estimate” of the power levels detected at a specified distance from the transmitting antenna. In all cases, the radiated power was too low to be detected on a RF hazard monitor. The power estimates listed are calculated from the spectrum analyzer amplitude reading corrected for antenna and cable loss. These are all seen to be well below the 3 milliWatts/cm² (900 MHz) and 8 milliWatts/cm² (2450 MHz) ANSI recommended maximum power. It is clear from these results that, within the validity of this current safety standard, all of the demonstrated microwave radiation levels are negligible.

The frame rate tabulated indicates the minimum time required between data transmission on a given lane. (CUTR qualifies this with the understanding that the listed value is subject to possible errors in
interpretation of the participant demonstration and the associated explanation.) Thus the maximum number of "handshakes" possible as a vehicle passes through the lane can be directly related to this number. The additional information needed is the amount of time that the vehicle is within the communication area of the transaction antenna. This effective communication area is very difficult to assess without an explicit, participant-assisted field measurement. It depends on the field of view of both the roadside antenna and the transponder antenna. It also depends upon the transmit power and the receiver sensitivity for both directions of communication flow. Since the measurement data set excludes sufficient information to accurately assess the length of the communication area for each participant along the direction of vehicle travel, the relationship to number of handshakes is illustrated with the following simple example.

Example Calculation of Number of Handshakes:

Assume the effective communication length along the direction of travel is 3 meters (chosen for illustration purposes only), the vehicle velocity is 20mph, and the frame rate is 5 micro-seconds.

The time that the vehicle is in the communication area \( t_c \) is given by:

\[
  t_c = 2.236 \times \frac{L_c}{v} \text{ (meters) / (mph)}
\]

where \( L_c \) is the effective communication length, and \( v \) is the vehicle velocity in miles per hour. For the given example:

\[
  t_c = 2.236 \times \frac{3}{20} = 335 \text{ micro-seconds}
\]

So, the maximum number of handshakes for a 5 micro-second frame period \( t_f \) is given by:
\[ N = \text{Integer}(t / t) = \text{Integer}(335 \text{ micro-seconds} / 5 \text{ micro-seconds}) = 67 \text{ handshakes} \]

The importance of determining the maximum number of “handshakes” is the subject of some debate. Some of the participants claimed that they reliably read/write all the necessary information with only one “handshake”. Others only take additional “handshakes” in the event that an error is detected in the digital data received, or for other reasons, a bad read is detected. Almost all participants stop communication between the roadside and the vehicle once a successful read has occurred. Consequently, multiple “handshakes” during system operation appears to be the exception, rather than the rule for effective ETC system operation.

The final parameter to consider is the bit rate. This parameter determines the rate at which information can be transferred to and from the roadside during an ETC transaction. This translates to the minimum time required to transfer the necessary information to and from the roadside. For example, for a transponder with a fixed data frame of 128 bits and a variable data frame of 128 bits, a total of 256 bits of information needs to be transferred. At a data rate of 9.6 kbps (i.e., 9,600 bps), the minimum time required to transfer 256 bits is given by:

\[ t = \frac{256 \text{ bits}}{9,600 \text{ bits per second}} = 26.67 \text{ milli-seconds} \]

With a higher data rate (e.g., 500 kbps), the time to transfer the same number of bits becomes:

\[ t = \frac{256 \text{ bits}}{500,000 \text{ bits per second}} = 0.512 \text{ milli-seconds} \]

Unfortunately, it is difficult to make more exacting conclusions regarding the impact of bit rate on ETC performance based on the results of the current evaluation. However, it can be stated that the higher the bit rate the greater the expected performance reliability under higher speeds (ETC express lanes), and the more compatible with other IVHS applications (traffic management, traveler information systems, etc.)

In summary, the field performance evaluations carried out allowed for some of the most relevant ETC electrical characteristics to be quantified and compared. The system implementations among the participants vary quite widely in terms of modulation techniques, communication protocols, antenna technology, and error control methods. Given the short time frame of evaluation, it was extremely difficult to draw specific relationships between the observed electrical characteristics and ultimate performance and reliability of a given ETC system. To be sure, the observed electrical characteristics are linked to performance, however, our experience suggests some caution in discounting a system based on a single electrical characteristic, rather the characteristic in question must be considered within the context of the entire system operation, under a longer evaluation period. Only then can a decision be made as to whether the characteristic is truly a key limiting factor, or actually represents a parameter with a safety margin.

VI. OTHER EVALUATION ISSUES

A. Health and Performance Factors

During the course of the ETC field performance evaluations, three areas of concern arose related to ETC health and performance factors.
Recently, national news relating to human health issues associated with exposure to electromagnetic fields (EMF) has captured widespread attention. EMF is briefly discussed below as related to the ETC power density levels measured during the field performance evaluations. Metal oxide windshields, and potential attenuation problems associated with metal oxide windshields, will also be addressed. Finally, ETC carrier frequencies, as related to the issue of FCC frequency allocation, will be outlined. Both metal oxide windshields and frequency allocation are issues which will affect the performance and reliability of ETC. This section of the report is intended only to provide background information regarding the three aforementioned ETC issues.

Electromagnetic Fields

The issue of human health factors is an appropriate concern in the use and exposure to RF technology in electronic toll collection. Questions are continuously being raised concerning the safety of radio frequency electromagnetic fields generated by ETC equipment. The RF frequency bands in the radio and microwave spectrum utilized for ETC are 902-928 MHz or 2400-2500 MHz. For these bandwidths, several organizational standards for power density fields have been established. For example, the American National Standards Institute standard (ANSI C95-1) is 3 milliWatts/sq.cm. for 850-950 MHz, and 8 milliWatts/sq.cm. for 2400-2500 MHz. The U.S. Occupational Safety and Health Administration standard (OSHA 1910.97), and the International Electrotechnical Commission standard (IEC 6570) is 10 milliWatts/sq.cm. Actual power density measurements taken during the field performance evaluations indicate a range of 47.5 nanoWatts/sq.cm. to 1.552 microWatts/sq.cm., below the national standards mentioned above for exposure levels. EMFs are commonplace, from the motors in refrigerators to the radiation from a computer or television screen to the very slight emissions from electric blankets. EMFs arise whenever an electric current is passed through a wire. The greater the current, the higher the fields. EMFs are silent, invisible waves that weaken with distance from their source. Most importantly, it must be pointed out that ETC is generally involved with radio transmission, or higher type frequencies with no electric or magnetic fields. The lower frequencies of EMF sources mentioned above create the electric and magnetic fields that are causing all the concern. Several previous studies have shown that exposure to EMFs increase the risk of certain types of cancer, but those studies have been non-conclusive and highly controversial. Researchers from UCLA and Southern California Edison recently completed (March, 1993) what has been termed the most comprehensive study to date on the effects of EMFs. They found that there is no link between increased cancer rates and exposure to electric fields.

Further, to put the ETC power densities into proper perspective, one need only to consider an increasingly common modern convenience, the portable cellular telephone. The associated total power radiated is about 300-500 micro-Watts for hand-held cellular phones, and up to 3 watts for car phones. Also, exposure time and distance from power source would be more of a concern in the case of the cellular phone. Exposure time is greater, and distance to power source is closer for the cellular phone user as compared to the ETC patron or operator.

Carrier Frequency Allocation

The partial spectrum listed in Table 6 illustrates a representation of the many different kinds of radio communications allocated near AVI broadcast frequencies. The information in the
<table>
<thead>
<tr>
<th>GOVERNMENT ALLOCATION (MHz)</th>
<th>NON-GOVERNMENT (MHz)</th>
<th>FCC USE DESIGNATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>902-928 Radiolocation</td>
<td>902-928</td>
<td>General Purpose Mobile (Amateur)</td>
</tr>
<tr>
<td></td>
<td>940-941 Mobile US116 US268</td>
<td>General Purpose Mobile</td>
</tr>
<tr>
<td>944-960</td>
<td>944-960 Fixed NG120</td>
<td>Auxiliary Broadcasting Domestic Public Fixed International Fixed Public Private Operational Fixed Microwave</td>
</tr>
<tr>
<td>Code</td>
<td>Definition</td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>------------</td>
<td></td>
</tr>
<tr>
<td>US116</td>
<td>no new assignments are to be made to Government radio stations after July, 1970, except on case-by-case basis.</td>
<td></td>
</tr>
<tr>
<td>US215</td>
<td>emissions for microwave ovens after 1980 must be confined to 902-928 MHz band.</td>
<td></td>
</tr>
<tr>
<td>US268</td>
<td>928-942 MHz band is also allocated to radiolocation service for Government ship stations provided they don't interfere with non-Government land mobile stations.</td>
<td></td>
</tr>
<tr>
<td>US218</td>
<td>bands 902-912 MHz and 918-923 MHz are available for Automatic Vehicle Monitoring (AVM) Systems provided the systems don't interfere with Government stations operating in these bands. AVM Systems must tolerate any interference from the operation of industrial, scientific, and medical (ISM) devices and operation of government stations authorized in these bands.</td>
<td></td>
</tr>
<tr>
<td>US267</td>
<td>prohibits ham radio operation in Colorado and Wyoming.</td>
<td></td>
</tr>
<tr>
<td>US275</td>
<td>band 902-928 MHz is allocated on secondary basis to ham radio provided they don't interfere with AVM systems.</td>
<td></td>
</tr>
<tr>
<td>US301</td>
<td>broadcast auxiliary stations licensed as of 1984 operating in band 942-944 MHz may continue on co-equal with other applications.</td>
<td></td>
</tr>
<tr>
<td>US302</td>
<td>concerns allocations in Puerto Rico.</td>
<td></td>
</tr>
<tr>
<td>G2</td>
<td>for bands 890-902 MHz and 928-942 MHz Government radiolocation is limited to military services.</td>
<td></td>
</tr>
<tr>
<td>G11</td>
<td>government fixed and mobile radio services are permitted in band 902-928 MHz on a secondary basis.</td>
<td></td>
</tr>
<tr>
<td>G59</td>
<td>for band 902-928 MHz, Government non-military radiolocation is secondary to military radiolocation.</td>
<td></td>
</tr>
<tr>
<td>707</td>
<td>band 902-928 MHz is designated for ISM applications.</td>
<td></td>
</tr>
<tr>
<td>708</td>
<td>bands 942-947 MHz and 952-960 MHz to mobile services is on a primary basis.</td>
<td></td>
</tr>
<tr>
<td>709</td>
<td>band 960-1215 MHz is reserved globally for airborne electronic aids.</td>
<td></td>
</tr>
</tbody>
</table>
As indicated, according to FCC, AVI technologies are assigned the 902-928 MHz band. Recently proposed rule changes for this band would, if adopted, segregate location and AVI services on different frequencies, broaden the range of services vendors could offer in this band, and possibly allow two or more location services to share the same portion of the band in the same market. The FCC believes interference from other sources is possible, but impossible to predict. Certainly it can be observed that this general bandwidth is becoming extremely crowded such that a vendor or operator can only wait for a problem to arise, then troubleshoot based on the frequency allocation illustration above.

According to the January 1993 issue of the IVHS America newsletter, the FCC and the National Telecommunications and Information Agency are considering four issues that have potential impact on the availability of radio frequency spectrum essential for IVHS purposes. First, the FCC has proposed to allocate 110 MHz of spectrum between 1.85 GHz and 1.99 GHz for personal communications services in the United States. This spectrum allocation could provide an additional source of the RF link in IVHS applications. Second, the FCC has proposed to rewrite its existing rules governing Private Land Mobile Services, and to re-allocate this band below 512 MHz. These rule changes could expand the capacity of this bandwidth below 512 MHz by almost 500 percent and create new channels for licensing over the next 10 years, enhancing the commercial deployment of IVHS. Third, the FCC proposes to allocate the 2310-2360 MHz band for satellite Digital Audio Radio Services (DARS) in the United States. Finally, the FCC has also proposed a U.S. allocation in accordance with the international allocation assigned for DARS. This allocation should facilitate international equipment compatibility for U.S. auto makers. Because radio-frequency spectrum matters usually involve extensive analysis as well as political negotiation, it has become imperative for spectrum management issues to receive coordinated attention from all IVHS applications, including ETC, which is to be expanded to electronic toll and traffic management.

Metal Oxide Film and Metal Oxide Film Windshields

Glass containing metal oxide film weakens electromagnetic signals passing through it. Interior transponders that were located just behind vehicle windshields during the ETC field performance evaluations did not provide for reliable read/write transactions. The Chevy Lumina van, was the only fleet vehicle with a metal oxide film windshield causing sufficient signal weakening (attenuation) to affect ETC transactions. Participants who selected not to place their interior transponder directly behind this windshield (all, except for AT&T which had attenuation problems as well), were thereby admitting the inability to reliably perform in this type of environment.

A metal oxide windshield contains a metal oxide film “laminated” between two pieces of glass. The most common films consist of silver oxide, which is vacuum sputter-deposited (sprayed on to provide for a uniform film thickness and consistency in several layers until 8-12 mils thick). Zinc or copper oxide coatings protect the silver oxide and prevent deterioration.

According to Southwall Technologies (Palo Alto, California), manufacturers of metal film, a metal oxide windshield will attenuate a 920
MHz signal 20-30 dB, or a power reduction of 1/100 - 1/1000 of the original interrogation signal (depending on the type of metal oxide film). Even though this magnitude of reduction appears low, it still affected the reliability of valid transactions during the field performance evaluations for the Chevy Lumina van. Further, there are four known manufacturers of metal film windshields: Troesch Autoglas AG (Switzerland); Libby-Owens-Ford (LOF) of Dayton-Toledo, Ohio; Pittsburgh Plate Glass (pPG) of Pittsburgh, PA; and Ford Glass (Carlite) of Detroit.

Table 7 lists U.S. auto glass manufacturers, selected brand names, and vehicles each brand is installed on. The brands do not include tinted glass, which looks similar to metal oxide film glass. Three common brand names for tinted glass were found on the evaluation fleet vehicles; Solar Ray, Soft Ray, and Flo-Lite. Tinted glass is composed of materials that filter out light but have little or no effect on electromagnetic waves at AVI frequencies. Heated windshields contain metal oxide film and are mentioned as well. Industry experts estimate
that about 2% of the U.S. fleet of vehicles currently have metal oxide windshields (probably higher for Florida), but no future trends on this issue could be obtained.

B. Recommendations for Further Evaluation

This very limited evaluation of ETC technologies has provided an assessment of basic operating characteristics and performance reliability. However, as time and budget constraints will allow, several areas of further research and evaluation would be desirable. In no order of importance these areas would include:

1. ETC operations fully integrated with hardware and software of upgraded FDOT conventional toll collection system, including (most importantly) automatic vehicle classification.

2. User preferences for ETC service features (particularly transponder type and placement), and review and assessment of ETC user perception surveys from other toll agencies, particularly those with existing ETC patrons.

3. Extension of ETC evaluations beyond single toll plaza passage to encompass monitoring and verification of points of entry and exit along the turnpike, as well as traffic management characteristics such as speed, volume, density, and incident detection.

4. Cost-effectiveness of commercial fleet management along the turnpike system.

5. Effects of alternative pavement markings, advance signage, and speed control techniques to accommodate ETC.


7. Variable pricing of toll fares through ETC in order to maximize turnpike and adjacent non-toll facility capacity during peak and non-peak travel times. This would include both increasing and decreasing tolls.

VII. CONCLUSIONS

Based on the findings of this evaluation, several very important conclusions can be listed as follows:

1. The total number of vehicle passes for this evaluation could not determine a statistically valid level of performance, however it did indicate that under CUTR's definition of "valid transactions", which includes VES, all participants would have difficulty achieving advertised performance levels (i.e., 99+%). CUTR believes this was primarily attributable to inadequate integration of VES and ETC, not necessarily inadequate VES technology.

2. Total "anomalies", which CUTR believes to be a good indicator of general readiness and preparedness for the rigors of this evaluation, resulted in success rates varying from a low of 70.8% to a high of 98.2%.

3. Invalid transactions (or the absence of valid transactions) which CUTR believes to be the true indicator of performance reliability within the environment of this evaluation, resulted in success rates varying from a low of 89.7% to a high of 98.4%.
4. Integrated violation enforcement capabilities was a general weakness exhibited by all the participants. The best participant performance resulted in 36% missing or bad photos. All of the other participants had between 44% and 68% of their photo opportunities resulting in missing or bad photos.

5. Discounting for the general weakness exhibited by all the participants in the VES component criteria of CUTR's definition of valid transaction, the modified indicator of performance reliability would consequently indicate the lowest rate of success to be 90.2%, and the highest rate of success to be 100%.

6. All participants were successfully able to demonstrate their specific operating characteristics in the field, as indicated in writing prior to their respective field evaluations. However, more extensive evaluations need to be conducted to further establish the relationship of these characteristics to performance capability and reliability. Generally speaking, it can be speculated that given a higher carrier frequency, faster frame rate, and higher bit rate; more data can be transmitted with the greatest reliability and least likelihood of interference.

7. The ability to consistently transmit through metal-oxide windshields was a problem for all the participants. Even though a relative small percentage of vehicles are equipped with these types of windshields, multiple transponder mounting locations (in addition to behind the front windshield) should be provided to rectify this situation.

8. During the "optional" evaluations: "Shadowing" was not a problem in recognizing both vehicles; however photos could not be produced for known violators, whether the leading or trailing vehicle. Anti-passback was achieved by all participants. Cross-lane recognition was a problem for several participants.

9. Based on CUTR's direct experience with this ETC evaluation and investigation into examinations of ETC performed by others, it has become apparent that a nationally-accepted, standardized field performance test should be established to evaluate (and "pre-qualify") ETC industry vendors. A common and comprehensive basis for comparative performance evaluations, prior to deployment, is needed with the rapid and continuous evolution of ETC. Most importantly, consistent standardized results-oriented information could be distributed throughout the toll industry.

10. The FDOT Turnpike office should proceed with its procurement process; however this report should serve as a general guide to weaknesses that apparently still exist in the ETC industry. In structuring its performance specification, FDOT should allow for flexibility in operating characteristics and sufficient time for performance acceptance testing.
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