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Embedded Radio Frequency Identification Device License Plates for Roadside Use in Nebraska

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Embedded Radio Frequency Identification Device License Plates for Roadside Use in Nebraska

by

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Embedded Radio Frequency Identification Device License Plates for Roadside Use in Nebraska

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The transportation industry has many stakeholders with different needs that work with advanced technologies. Radio Frequency Identification (RFID) is an emerging technology that is used to track inventory and it holds promise for the transportation industry. This research identifies how to evaluate transportation stakeholder requirements for RFID technologies using a tool described as the House of Quality (HOQ). This research investigates RFID's ability to work in license plates and may provide infrastructure to support identifying RFID enabled commercial vehicles. This research considers variables that affect the performance of a RFID License Plate System that will use a scanner located at roadside locations. This research also proposes an Analytic Hierarchy Process (AHP) decision model for selecting the product that is "best" for RFID roadside use in Nebraska with commercial vehicles.

DEDICATION

This dissertation is dedicated to Dr. Patrick T. McCoy, who provided me with the direction and insight to undertake such an arduous task, and Ms. Gwendolyn Johnson, who constantly reminded me of my goals. You both are gone but not forgotten. I would also like to dedicate this body of work to the Wagner family in Lincoln, NE, you made a strange and faraway place seem like home. I'll never forget the invaluable time spent with Pops learning about life, love, and happiness.

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I would like to acknowledge my strength, Quaynteece. You, the boys, and Apasra are my breath and life would be impossible without you. Mom, I'd like to thank you for leading the way, and you too Dad for getting me there by being a man of few words, but always plenty of action. I would like to thank the Alfred P. Sloan Foundation and the UNL Richard H. Larson Fellowship for financial support. A heartfelt appreciation goes to Michelle Simpson who was instrumental in recruiting me to the University of Nebraska-Lincoln. Thank you to my committee members Dr. Laurence Rilett and Dr. Anju Sharma. I would like to especially thank Dr. Aemal Khattak and Dr. Erick Jones; this would not be possible without the guidance and instruction from you both.

GRANT INFORMATION

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DOT Federal Motor Carrier Safety Administration Nebraska Department of Motor Vehicles (DMV) “Evaluation of RFID Technologies for Roadside Safety”

Mid American Transportation Center (MATC), “Evaluation of RFID Technologies for Linear Roadside Assets”

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CHAPTER 1 INTRODUCTION

The transportation field is comprised of many industries with different needs that work with advanced technologies. Radio Frequency Identification (RFID) is an emerging technology which has been introduced into the transportation system as a more efficient means of capturing data in comparison to manual "screening" approaches for enforcement of safety and registration guidelines. A major challenge for the transportation industry is to investigate and test the feasibility of emerging technologies such as RFID.

"Every successful company has used data and information to help in its planning processes. They look at field test data, comparing their product to that of their competitor's product. Condemningly, an excessive amount of this information is often left unfinished. It [field test data] is frequently examined as individual data, without comparison to other data that may support or contradict it" (Johnson). Customer needs and wants for a product's quality commonly is evaluated using a tool described as the House of Quality (HOQ), which is a form of Quality Function Deployment (QFD). The HOQ tool helps to alleviate the unfinished information that is left out of a product comparison. RFID use for certain transportation projects can be evaluated using HOQ to determine priorities of transportation stakeholder needs. Stakeholders can include Carrier Enforcement, Department of Motor Vehicles, State Intelligent Transportation Division, State Transportation Planning Division, State Patrol, as well as trucking companies and other transportation users.

RFID tags have been used for transportation toll systems since the early 1970s (Jones). Transponder or tag-based Radio Frequency systems have been utilized for weigh stations and other enforcement actions over the last several decades with systems such as Pre-Pass and NorPass. Enforcement operations have a critical need for improved operations because random screenings do not allow for the correct attention to be placed upon those carriers and vehicles most likely to be in violation of the law. These random screenings can be an inefficient use of enforcement resources if violations aren't caught. Enforcement capabilities and resources can be improved with modern data collection technologies. To utilize automated technologies for more effective roadside enforcement, pertinent information must be accessible and collected in a reliable way. The idea of using one RFID based system that can be integrated for use with both RFID toll systems, other transponder based systems, and additional state systems that can utilize common information is the foundation for this research. Such a system can be created with standardized RFID tags embedded in license plates that can be scanned or read by a reader installed alongside a roadway, for example on a mile marker. This idea allows states to expand extra scanning capacity for the system in an incremental manner using existing readers that interrogate other transponders to read the common information based on an official standard. For this type of system to be successful, testing of multiple aspects has to take place. One such aspect is the RFID reliability or whether or not the system will read consistently enough for this option to possibly be used for commercial vehicle operator (CVO) trucks to be identifiable at the roadside automatically.

This research tested the RFID technology’s ability to work in license plates to make information collection for CVO more efficient, while combining the idea of identifying key product attributes necessary to satisfy transportation stakeholder concerns for a RFID based license plate system.

CHAPTER 2 RESEARCH QUESTIONS, OBJECTIVES AND HYPOTHESES

The purpose of this research was to conduct a feasibility study to embed RFID in license plates to improve the efficiency of data capture for CVO. It can eventually be used to develop Nebraska's Commercial Vehicle Information Systems and Networks (CVISN) program. CVISN is trying to improve safety and efficiency by giving enforcement officers the information they need, and by screening entities on the road electronically so that safe and legal drivers/carriers have expedited trips.

It is shown that RFID readers can perform well in transportation operations with simple egress and ingress operations such as toll road systems. Vendors such as Mark IV, 3M, Transcorp (electronic registration), Motorola and SAVI have utilized this type of active RFID technology for robust operations such as port security container tracking (e-seal products). The development of this technology within license plates provides an innovative step in the research area along with providing a strong practical use for Nebraska State agencies and CVOs to support information capture at roadside check stations as well as intermittent capture points. It is envisioned that once successful development of the RFID technology in license plates is realized, RIFD readers can be placed at mile marker checkpoints that will support more real-time tracing of CVO information. Information needs such as vehicle inspections, road usage, and road speed information can be captured and effectively managed to facilitate CVO and state operational efficiencies.

Because this research requires Nebraska Department of Motor Vehicles (NEDMV) to provide requirements on utilizing RFID license plates to assist with CVISN objectives at the roadside, the research will require cooperation between the University of Nebraska (Transportation Center and Radio Frequency Supply Chain Logistics (RfSCL) lab), the NEDMV, the Nebraska Department of Roads (NDOR), The Nebraska Department of Corrections, Cornhusker State Industries (CSI) and the Nebraska State Patrol (NSP) to perform a stakeholder analysis, and RFID license plate prototype testing.

2.1 Research Questions

The overall goal of this initiative was to assist with the selection of developing a system capable of providing accurate, real time information to government agencies at a marginal cost to the users. The secondary goal of the research is to investigate the viability of embedding RFID tags into license plates so that readers strategically located alongside streets and roads can capture information. The main objective of the research is to study the issues; technical and political, related to embedding RFID tags into Nebraska motor vehicle license plates. To meet this objective the following research questions need to be answered:

- Can a RFID transportation stakeholder analysis can be performed to facilitate selection of appropriate RFID equipment for Nebraska's identified needs?
- Can RFID tags be imbedded into license plates and then be used to facilitate automatic vehicle data capture?

2.2 Research Objectives

To investigate these questions three specific objectives were completed:

- Specific Objective #1: Evaluate multiple transportation stakeholder requirements for automated technologies.
- Specific Objective #2: Provide a decision model using multi-criteria decision analysis for equipment selection.
- Specific Objective #3: Evaluate current RFID technology for use at roadsides.

For specific objective #1 evaluating transportation stakeholder's requirements for automated technologies, this research investigated and quantified which RFID parameters, such as technology reliability, accessibility, functionality, etc. are important to transportation stakeholders in the state of Nebraska. A quality functional deployment process or a "house of quality" tool was used for this investigation. A successful identification of stakeholder requirements will indicate completion of objective #1.

Specific objective #2 provides a decision model using multi-criteria decision analysis for the selection of RFID equipment. This research utilized an Analytic Hierarchy Process (AHP) model to simulate the value of utilizing one RFID technology in lieu of another. The successful completion of the AHP analysis will be determined by the consistency ratio for each individual stakeholder analysis. A ratio greater than 0.1 indicates there is inconsistency in the customer preferences. If the majority of the AHP models are consistent then objective #2 is successfully completed.

For specific objective #3 evaluating current RFID technology for use at roadsides, the research measured the reliability rates for RFID technologies. The reliability measurements were based on a sequential design of experiment setup focused on received signal strength and distance from transponder. Successful completion of this objective occurs when all hypotheses have been tested.

2.3 Hypotheses

The hypotheses statements were derived specifically from the research objectives. The Design of Experiments (DOE) was tested using the analysis of variance at a 95% confidence level using the test statistic:

$$F = \frac{\left(\frac{R^2}{k}\right)}{\frac{(1 - R^2)}{(n - (k + 1))}}$$

The decision rule is:

If F ≥ the critical value at n degrees of freedom, where n is a number, then conclude that H_0 is rejected. If H_0 is rejected then H_a must be accepted. The critical values for the F distribution can be found in Appendix A.

The following hypotheses were tested:

1. H_0 = The independent variable tag location has no statistically significant effect on the dependent variable Received Signal Strength Indication (RSSI).

   H_a = There is a statistically significant effect of tag location on RSSI.

2. H_0 = The independent variable horizontal distance has no statistically significant effect on the dependent variable RSSI.

H_a = There is a statistically significant effect of horizontal distance on RSSI.

3. H_0 = The independent variable vertical distance has no statistically significant effect on the dependent variable RSSI.

   H_a = There is a statistically significant effect of vertical distance on RSSI.

4. H_0 = The independent variable antenna height has no statistically significant effect on the dependent variable distance.

   H_a = There is a statistically significant effect of antenna height on distance.

5. H_0 = The independent variable tag height has no statistically significant effect on the dependent variable distance.

   H_a = There is a statistically significant effect of tag height on distance.

CHAPTER 3 BACKGROUND

3.1 RFID Technologies

RFID technologies originated from radar theories that were discovered by the allied forces during World War II and have been commercially available since the early 1980's (Landt). Over the last two decades, RFID has been used for a wide variety of applications such as highway and bridge tolls, livestock tracking, transportation freight tracking and motorcycle manufacturing. Until recently, the technologies were considered expensive and limited, but as the tags, readers, and the associated equipment costs continue to decrease, a growing number of organizations have begun to explore the feasibility of using RFID systems (Jones).

3.1.1 RFID Operations

A standard RFID system consists of a tag, reader, and middleware software (Figure 1). Tags often consist of a microchip with an internally attached coiled antenna. Some tags include batteries, expandable memory, and sensors. A reader is an interrogating device that has internal and often times external antennas that send and receive signals. The middleware software allows the system read/write tags and provides a means to catalog and query tag information.

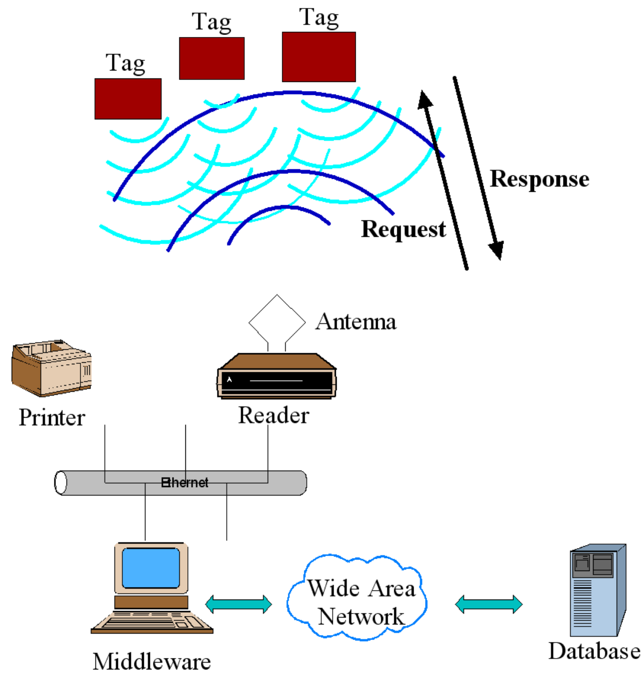

Figure 1. Typical RFID System (Thompson)

3.1.2 Classification of RFID Tags and Readers

RFID tags and readers can be grouped under a number of categories. Their classifications are presented in Tables 1 and 2.

Table 1. Classification of RFID Tags (Ilie-Zudor)

Category	Criteria	Description
Power	Passive	Also called ‘pure passive’, ‘reflective’ or ‘beam powered’ Obtains operating power from the reader The reader sends electromagnetic waves that induce current in the tag’s antenna, the tag reflects the RF signal transmitted and adds information by modulating the reflected signal
	Semi-passive	Uses a battery to maintain memory in the tag or power the electronics that enable the tag to modulate the reflected signal Communicates in the same method, as the other passive tags
	Active	Powered by an internal battery, used to run the microchip’s circuitry and to broadcast a signal to the reader Generally ensures a longer read range than passive tags More expensive than passive tags (especial because usually are read/write) The batteries must be replaced periodically
Memory Type	Read-only	The memory is factory programmed, and cannot be modified A very limited quantity of data can be stored, usually 96 bits of static information Can be easily integrated with data collection systems Typically are cheaper than read-write tags
	Read-write	Can be read as well as written into Its data can be dynamically altered Can store a larger amount of data, typically ranging from 32 kB to 128 kB Being more expensive than read-only chips, is impractical for tracking inexpensive items
Communication Method	Induction	Close proximity electromagnetic, or inductive coupling—near field Generally use. LF and HF frequency bands
	Propagation	Propagating electromagnetic waves—far field Operate in the UHF and microwaves frequency bands

Table 2 - Classification of RFID Readers (Ilie-Zudor)

Category	Criteria	Description
Function of the Device	Read	Only reads data from the tag Usually a micro-controller-based unit with a wound output coil, peak detector hardware, comparators, and firmware designed to transmit energy to a tag and read information back from it by detecting the backscatter modulation Different types for different protocols, frequencies and standards exist
	Read/write	Reads and writes data from/on the tag
Fixation of the Device	Stationary	The device is attached in a fixed way, for example at the entrance gate, respectively at the exit gate of products
	Mobile	In this case the reader is a handy, movable device.

3.1.3 RFID Applications and Vendors

Table 3 lists some current and proposed uses of RFI. The applications span a wide spectrum of markets and a full comprehensive overview would certainly surpass the limits of this research.

Application	Location	Tags
Military	Assets, consumables, conveyances, vehicles	Smart seals, RTLS, RFID with sensing
Smart and Secure Tradelanes global initiative	Intermodal containers, etc.	Smart seals and RTLS
Other Logistics	Items, assets, conveyances, vehicles	Active, active with sensing, RTLS, SAL
Passenger transport/automotive	Vehicle, premises and computer access, vehicles, ticketing, assets	Key fobs, etc., active with sensing, RTLS, SAL
Prison (correctional facility) and parole service	People	Smart wrist and ankle bands
Consumer goods and retail	Items, assets, conveyances, vehicles	SAL, e.g. self-adjusting use by date, in-transit condition monitor
Postal and Courier	Assets, consumables, conveyances, vehicles	Smart seals, RTLS, RFID with sensing
Healthcare	People, assets, conveyances, vehicles	Active, active with sensing, RTLS, SAL
Secure access/other security and safety	Various	Various
Animals, farming, research, libraries, archiving, leisure, manufacturing, financial and other	Animals, people and things	Condition monitoring tags, asset tags, RTLS, etc.

Table 3. RFID Applications

IDTechEx believes that in the next decade, most of the active RFID market will be in the automotive, transportation, logistics, healthcare and military sectors. With all this potential it is little wonder that the number of users and suppliers of active has increased. Table 4 gives some examples, with the location and tracking of conveyances, packages and assets receiving the most attention.

Table 4. RFID Applications and Vendors (IDTechEx)

Sector	Location	Examples of Application	Examples of Suppliers
1. Containers, packages and assets	Intermodal transport containers	International freight by land and sea; Tracking or tamper alerting seals; Precise location.	Savi Technology; WhereNet; Universal Guardian; Identec Solutions
	Air Unit Load devices; ULDs	Air freight	Savi Technology; Identec Solutions
	Other containers, packages and assets	Tracking, tracing, condition monitoring	Airbee, Cambridge Consultants, Power ID (Power Paper), Infratab, Microlise, Ubisense, Axcess, Savi Technology, Maxim Dallas Semiconductor, Parco Wireless, KSW Microtec, Innovision, Alien Technology, Lintec, DNP, Toppan Printing, Miyake, LITI, Yoshikawa, DatatagID (Mitsui), Nedap, Comtec Telecommunications Corp, Active RFID Systems (Winsong Productions), LG, Samsung, Assa Abloy, SandLinks, Atlantic, Ekahau, PanGo Networks, Motorola, Wherify, Pinpointers, AWAREA, Tagtec, Cirronet, Mitsubishi, Siemens, Telegesis, Escort Memory Systems, Lyngsoe, Avery Dennison, Texas Instruments, Symbol Technologies, RSI ID, MaxID/Sygade, Sirit, Identec Solutions, Wavetrend, Intel, Sandia National Laboratories, Sealed Air Corporation, Bio-RFID Solutions, Graphic Solutions, ActiveWave, 24-7 Safety Systems, Syscan, Sensitech, A3 Technologies, Tagcorp, Pepperl + Fuchs, Avante, AWID, Trenstar, SAIC, Parsons Brinkerhoff, EM Micro, Shaw Industries, Fiatech, Idensys, eXI Wireless (now Verichip), Scan Pak, Cegelec AEG, ICE Automation, WhereNet, HealthCare Pilot, Microsoft
2.Telecommunications	RFID enabled cellphones	Purchases, transport ticketing	Nokia/Innovision, Sony Ericsson, NTT DoCoMo, Samsung, LG, Motorola, Sanyo, Connexion2
3. Vehicles	Cars and trucks	Non stop road tolling and tracking	TransCore, Sirit, Avonwood, Hills Numberplates, Mark IV Industries, Denso Corporation, Pinpointers, VehicletrackingLtd, Tracker
	Airport Ground Support Equipment; GSE	Tracking, status	TransCore, IBM/ SITA
	Vehicles and their trailers and containers used in manufacture, warehousing and logistics	Tracking, status	WhereNet, Avonwood, Q Track Corporation, SandLinks, Power ID
	Bicycles	Autostore, antitheft	Wavetrend, Bluelon
4. People	Prisoners, parole, hospitals, care homes, vulnerable invalids, visitors to leisure facilities, theme parks, etc.	Tracking, error prevention, safety, security including secure access, purchases	Xmark (Verichip), AlancoTechnologies, Radianse, ELPAS, SafeTzone, RFCode, Parco Wireless, Ubisense, Connexion2, Bluelon, SandLinks, Wherify, Pinpointers, AWAREA, Axcess, Tunstall Telecom, HealthCare Pilot
5. Remote locking of cars; "Car clickers"	Key fobs	Convenience, security	Texas Instruments, Philips
6. Ubiquitous Sensor Networks	Chips or labels	Disaster alerts and monitoring, military eavesdropping, traffic management, etc.	LG, Samsung, Intel, DNP, Telegesis

3.1.4 RFID Frequencies and Characteristics

Figure 2 shows some frequency bands in which RFID systems operate. The number of times the signal repeats itself per second, the frequency, varies widely in differing RFID systems. Frequency is measured in Hertz (Hz): one Hertz is one cycle per second or 60 revolutions per minute (rpm).

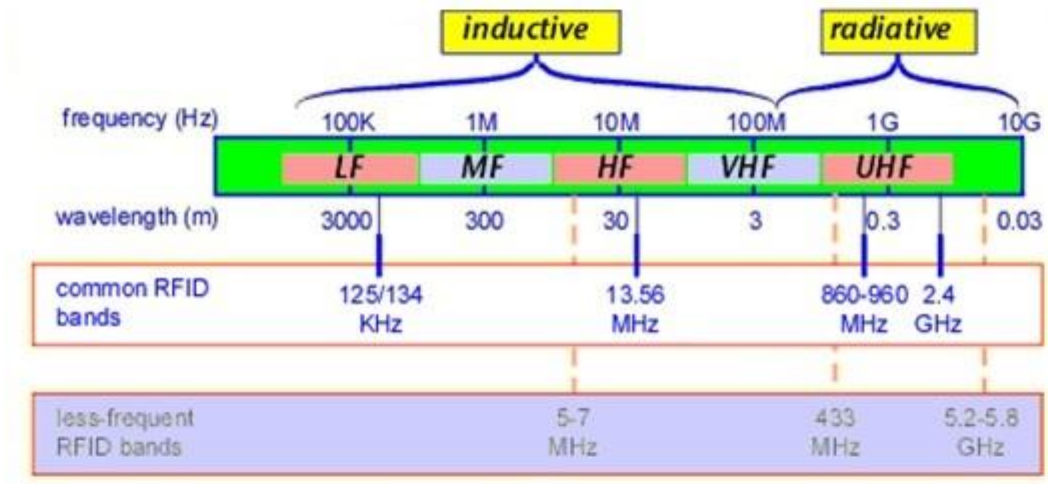

Figure 2. RFID Frequencies (Ward)

Several issues are involved in choosing a frequency of operation. The most fundamental, as indicated in the diagram, is whether inductive or radiative frequencies will be used. The type of frequency used is closely related to the size of the antennas used relative to the wavelength. When the antennas are very small compared to the wavelength, the effects of currents flowing in the antenna cancel so there is no radiation. Radiative systems use antennas comparable in size to the wavelength. The very common 900 MHz range has wavelengths around 13 inches. Reader antennas vary in size from around 4 to > 12 inches, and tags are typically 4-7 inches long. These systems are not limited by reader antenna size but by signal propagation issues.

In the mid-1980's the United States Federal Communications Commission (FCC) allocated certain frequency bands in which unlicensed operation were allowed. RFID systems are typically operated in these unlicensed bands. The 900-MHz Industrial, Scientific, and Medical (ISM) band is a very common frequency range for UHF RFID readers and tags. It is important to note that bands do not exist in isolation. Figure 3 shows the various uses in the United States for equipment that operated with frequencies near the ISM band.

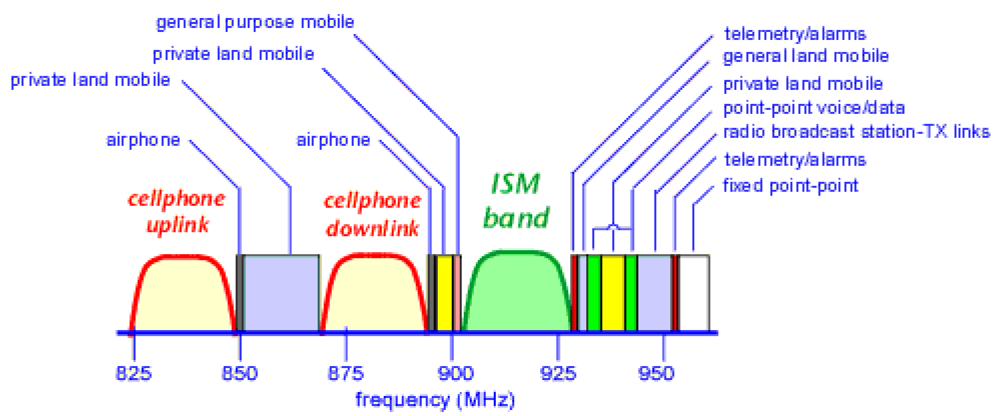

Figure 3. Frequency Spectrum Use Summary (NTIA-OSM)

Other users of the ISM band may also interfere with RFID readers, or encounter interference due to them: examples are cordless phones and older wireless local area networks. The frequencies used in RFID systems typically fall in the following ranges:

- 125-134 kHz: This is the low frequency which allows the detection of RFID tags in a distance of less than 0.5 meter. This frequency is used for animal identification on farms, zoologists, and by veterinarians.
- 13.56 MHz: This frequency allows the detection of RFID tags for a distance of up to 1.5 meters. This frequency is used for applications related to access and security.
- 433-956 MHz: The frequencies at the range from 433 to 864 allow the detection of RFID tags for a distance of up to 100 meters while the frequencies at the range from 865 to 956 MHz allow the detection of RFID tags for a distance which varies from 0.5 to 5 meters. The frequencies at this range are used for applications in logistics.
- 2.45 GHz: This frequency enables a RFID reader to detect a tag from a distance of 10 meters. The specified frequency is used for applications related to mobile vehicle toll.
- 5.9 GHz: Frequencies in this range are normally used for outdoor applications due to the radiative strength of this allocated spectrum.

The circuitry inside the tag is what receives the energy transmitted from the transponder and then powers the chip and then backscatters the chip data back to the reader. The main two types of tags used for this research are passive and active. Passive RFID tags are typically made of metal and plastic with a single integrated circuit. Sometimes the tags are incorporated into a printable label; in other cases the tag has its own adhesive and is attached directly to an object. Tags come in a variety of shapes and sizes, as shown in Figure 4.

Figure 4. RFID tags

The visible part of a tag is the antenna structure. The antenna structure is often made of conductive material such as copper, which is plated and patterned on a substrate. Active tags (Figure 5) are made of the same materials as passive tags with the exception of a battery operated circuit. The battery power allows the tag to be read from farther distances than a passive tag.

Figure 5. Example of a small active tag

3.2 Quality Function Deployment

A Quality Function Deployment (QFD) tool uses a matrix process to collect a number of issues that are essential to the planning process. The House of Quality Matrix is a widely used form of this method among Six Sigma professionals. This method is used for translating customer or stakeholder requirements into a functional design.

Major characteristics of QFD as a quality system are as follows; First, QFD is a quality system that integrates elements of systems thinking, e.g. (viewing the development process as a system) and psychology (being able to conceptualize customer concerns, what value is being determined, and how customers or end users become interested, choose, and are finally satisfied) . Second, QFD is a quality method of determining the needs of the customer, choosing how to execute which features to incorporate into the product, and to what level of degree pertaining to performance. Third, the QFD quality system is a strategy for competiveness. It maximizes positive qualities that add good worth. It brings out outspoken and unspoken customer needs or request and translate them into technical injunction. Then they're prioritized and directed so that the contributor can optimize those features that will bring the greatest competitive advantage. Finally, QFD is the only comprehensive quality system targeted specifically at satisfying the customer completely through the development and business processes from beginning to end.

3.3 Making Decisions for Implementation of RFID

With several Intelligent Transportation Systems (ITS) options available one must determine which system is the most effective for a specific application. The systems can easily be compared by costs however, it is unclear as to what level of reliability and productivity is present with each option. Since there is more than one factor present to base the decision on, a Multiple Criteria Decision Analysis (MCDA) technique is necessary. MCDA is a collection of decision techniques that allows the decision maker to make a single choice from a set of alternatives whose attributes are known with certainty (Dyer et al.). Many problems that are evaluated using MCDA can be formulated as mathematical programming problems. When risk or uncertainty plays a significant role in the assessment of the alternatives, a similar set of techniques is applied. These techniques, known as Multi-Attribute Utility Theory (MAUT), focus on the structure of multiple attributes alternatives and methods for assessing subjective probabilities (Dyer et al.). These types of techniques often include a sensitivity analysis in the assessment.

There are several techniques for decision analysis available within the MCDA family.

The two main categories of MCDA techniques are outranking methods and utility-based methods (Polatidis et al.).

Pirlot characterizes outranking methods by the degree to which a disadvantage is compensated by advantages (Pirlot), and goes on to state that several of these methods are classified as non-compensatory procedures and small differences in preference may be compensated by preferences in favor of the other alternative. This means that only substantial differences between comparisons are meaningful in outranking methods. Examples of outranking methods include: Elimination Et Coix Traduisant la Realite (ELECTRE) (Roy & Vincke), Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) (Brans & Vincke), and Regime Method Analysis (Nijkamp et al.). While outranking methods can lead to some pairs of alternatives that are incomparable, utility function-based methods allows for all criteria to be directly comparable (Polatidis et al.). These methods provide a single score for each alternative that can be used to derive a final decision. Examples of utility based methods include: Multi-Attribute Utility Theory (MUAT) (Keeney & Raiffa), Simple Multi-Attribute Rated Technique (SMART) (von Winterfeldt & Edwards), and Analytic Hierarchy Process (AHP) (Saaty). Based on the customer requirements and technical characteristics (discussed in Chapters 5 and 6) of the RFID system needed for roadside use, the Analytic Hierarchy Process (AHP) was selected for further evaluation.

CHAPTER 4 METHODOLOGY AND RESEARCH PLAN

4.1 Methodology

This study used the Design of Experiments (DOE) methodologies. The basic principles of DOE are replication, randomization, and trying to increase the precision of the experiment by making comparisons among the conditions of interest. Some of the benefits of DOE include its aim at changing the process for better performance, established mathematical foundations, and yielding the maximum amount of information for a given amount of data (Goh). These compound models are necessary to quantify effects and can be used to predict future responses (Bjerke et al.). From the DOE a research method derived in the RFID Supply Chain Laboratory (RfSCL) at the University of Nebraska RfSCL called Design for Six Sigma Research (DFSS-R) was utilized (Figure 6). It is based on a Plan-Do-Check-Act (PDCA) strategy and is a hybrid version of common Six Sigma and Design for Six Sigma (DFSS) methods (Yang and El-Haik). This technique is the fusion of traditional research methods with industry's new gold standard, Six Sigma, into a continuous improvement methodology described as DFSS-R.

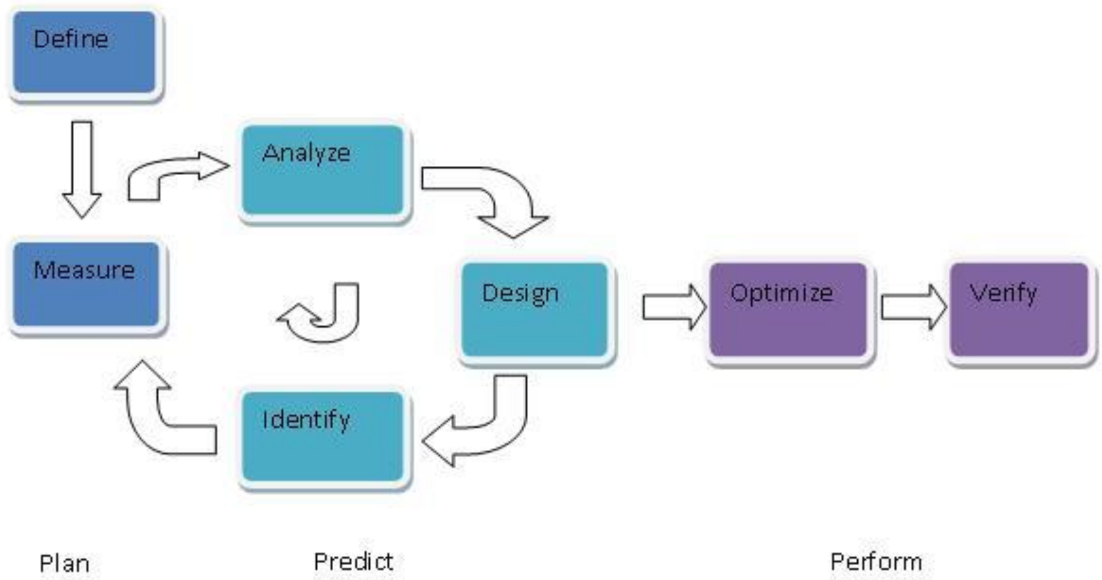

Figure 6. Design for Six Sigma Research Plan

The advantage of this methodology over quality initiatives is that it applies statistical techniques not only to product quality, but also many aspects of business operations improving the overall organizational efficiency. The distinction "Six Sigma" originates from statistical terminology. In statistics sigma (σ) commonly represents the standard deviation of a random variable. Given a normal distribution curve, the probability of falling within a plus or minus six standard deviations from the mean is approximately 0.9999966. It is more commonly expressed in production processes as a defective rate for processes that will be 3.4 defects per million units (Yang). The objective for Six Sigma methodologies is to reduce the operational variation to achieve small process standard deviations. The Six Sigma methodology is based on recognition by many companies as a means for reducing defects, increasing company productivity and improving company profitability. Six Sigma can be considered as an extension of Total Quality Management (TQM) initiatives.

This methodology is based on a strategy to develop operational prototypes and is organized into a Plan, Predict, and Perform (3P) Model (Figure 7) that utilizes 7 steps: Define, Measure, Analyze, Identify, Design, Optimize and Verify (DMAIDOV).

Figure 7. Plan, Predict, Perform

To conduct a thorough investigation into the possibility of embedding RFID chips in license plates and its future implementation, all phases of this model will be used in this research as depicted in Figure 7. In the first phase the problem is defined and accurate metrics are set up. In the predict phase an analysis is made, relevant technologies identified and then a design formulated. In the last phase of the model tests are conducted in real life situations and then the technology is validated.

4.2 Research Plan

The research plan consists of investigating the aforementioned research objectives in order to answer the research question. The research plan follows in the order of the research objective and the step labeled in the methodology.

4.2.1 House of Quality

For the first research objective HOQ analysis was used. This analysis is more focused based on the outcomes of the QFD. The general structure of House of Quality is provided in Figure 8.

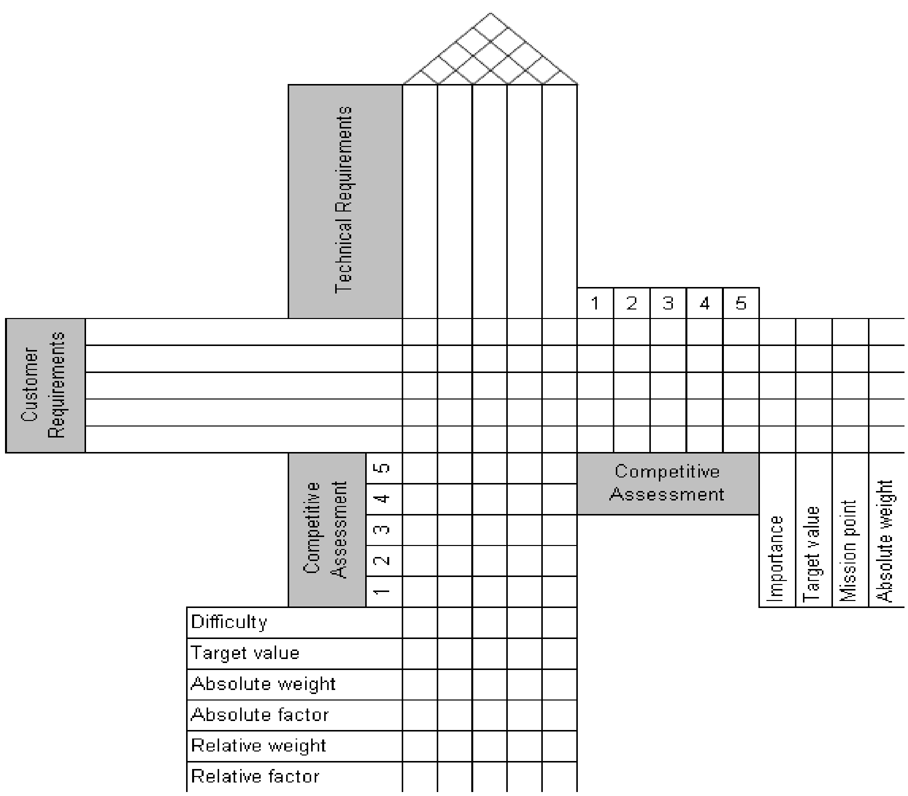

Figure 8. General House of Quality Structure

The steps to developing a QFD are as follows:

- Develop a list of customer requirements
- Develop a listing of technical design elements along the roof of the house
- Demonstrate the relationships between the customer requirements and technical design elements
- Identify the correlations between design elements in the roof of the house
- Perform a competitive assessment of the customer requirements
- Prioritize customer requirements
- Prioritize technical requirements
- Final evaluation

In Figure 8, the left side of the HOQ shows the customer requirements and the right side shows the result scores for meeting the requirements, while the top shows the technical design requirements. The tool takes customer preferences and demands and then turns them into technical requirements that can be quantified, measured, and analyzed.

The next category is competitive assessment rooms. These rooms are located on the matrix where benefit rankings and ratings are assembled for analysis. The rankings provide a prioritization of customer requirements while the customer competitive assessment allows to spot strengths and weaknesses in both the product and the competition's products."(Squires).

Once this has been completed the next phase of the HOQ is the relationship matrix. During this task the approach is, "What is the coalition between this specific 'how' and this specific 'what'?"(Squires) The researcher must ask the question is there a difference between the two, is there cause and effect between the two, or is this decision is neutral within the group? Based on the group decision, the researcher assigns a strong, medium, weak or no relationship value to this specific "what/how" pairing. This process continues until all "what/how" pairings have been reviewed.

Once the relationships matrix room has been completed, the researcher can then move on to the absolute score and relative score rooms. Based on the importance ratings and the relationship matrix values, the researcher calculates the absolute and relative scores. The calculations are the researcher's best estimate as to which product performance measures ("hows") have the greatest impact on overall customer satisfaction (Squires). The relative and absolute weights for technical requirements are evaluated to determine what decisions need to be made to improve the design based on customer input, then computing a percentage of weight factor for each of the absolute weight and relative weight factors.

4.2.2 Analysis of Variance (ANOVA)

For the reliability and testing the factorials of the experimental design analysis of variance is used ANOVA (Neter). ANOVA is used to explain the effect of more than one factor on differences in the dependent variables of the experiments. The parameters used in ANOVA can be explained as follows:

DF is degrees of freedom for a full factorial design with factors F1, F2 and F3. SS is the abbreviated form of sum of squares, which is the sum of squared distances from the measurements. SS Total is the total variation in the model. SS (F1), SS (F2), and SS (F3) are the deviation of the estimated factor level mean around the overall mean. They are also known as the sum of squares between treatments. SS Error is the deviation of an observation from its corresponding factor level mean.

Seq SS is sequential sum of squares. Minitab version 16, which is the statisical computational software used for this research, breaks down the SS Regression or treatments component of variance into sequential sums of squares for the main effects, interactions, and each covariate. The sequential sums of squares depend on the order the terms are entered into the model. It is the unique portion of the sum of squares explained by a term, given any previously entered terms.

Adj SS is adjusted sum of squares. Minitab also breaks down the SS Regression or Treatments component of variance into the adjusted sums of squares for the main effects, interactions, blocks, and each covariate. The adjusted sums of squares do not depend on the order the factors are entered into the model. It is the unique portion of SS Regression explained by a factor, given all other factors in the model, regardless of the order entered into the model.

Adj MS is adjusted mean square. The calculation for the adjusted mean square for the model terms is

$$AdjMS = \frac{AdjSS}{DF}.$$

The Fishers test is a statistical way to determine whether the interaction and main effects are significant. The formula for the model terms is $F = \frac{MS(Factor)}{MS(Error)}$. The degrees of freedom for the test are numerator = degrees of freedom of factor and denominator = degrees of freedom for error. Larger values of F support rejecting the null hypothesis that there is not a significant effect.

P is the p-value. It is used in hypothesis tests to help decide whether to reject or fail to reject a null hypothesis. The p-value is the probability of obtaining a test statistic that is at least as extreme as the actual calculated value, if the null hypothesis is true. A commonly used cut-off value for the p-value is 0.05, which corresponds to 95% confidence. For example, if the calculated p-value of a test statistic is less than 0.05, reject the null hypothesis.

S is an estimated number of α (type I error), the estimated standard deviation of the error in the model. Note that S^2 = MS Error.

R squared (R^2) is the coefficient of determination, and indicates how much variation in the response is explained by the model. The higher the R^2, the better the model fits the data. The formula is $R^2 = 1 - \frac{SSError}{SSTotal}$.

4.2.3 The Analytic Hierarchy Process

AHP, which is a popular technique based upon pairwise comparisons, successfully meets all the requirements set forth in the problem. Vargas attributes the successfulness of AHP to being a consequence of its simplicity and robustness. AHP was created to assist in the decision making process when a large number of interrelated factors is involved. It allows for the inclusion of human intuition and subjective judgments into the decision making process (Shapira & Goldenberg). AHP can be easily applied to group decisions where individual judgments are combined to make an overall decision (Ahmad et al.). In most situations a group or team of individuals is responsible for making a choice between alternatives rather than a single individual. There may be cases where someone is biased towards a particular alternative or input is gathered from several people, but it is not ideal to give them equal weight. For instance, the group decision may be more heavily weighted towards the DOT's personnel preferences because the changes would affect them the most. The addition of a group decision adds another step in the decision making process. Once individual preferences or choices are obtained, they must be combined in some way to achieve the group's overall preference (Keeney & Raiffa, 1976).

There are five fundamental steps in AHP:

- Constructing the hierarchy
- Making pairwise comparisons
- Determining relative weight calculations
- Aggregating the relative weights
- Verifying consistency in the comparisons

Step one in AHP consists of decomposing a complex problem into a heuristic map that clearly shows the scope of the problem. Heuristics methods such as AHP are appealing due to their ability to quickly evaluate difficult problems by producing near-optimal solutions (Dyer et al., 1992). Heuristics can be used to simplify the problem by generating levels of attributes and alternatives.

CHAPTER 5 RESEARCH OBJECTIVE #1

By using the DFSS-R Methodology the first objective was investigated and the PLAN portion of the Methodology by utilizing the aforementioned HOQ/QFD methods was completed.

5.1 HOQ/QFD

A Quality Function Deployment tool (QFD) uses a matrix process to collect a number of issues that are essential to the planning process. The House of Quality Matrix is highly recognized and widely used form of this method. This method is used for translating customer or stakeholder requirements into a functional design. Collecting information from transportation stakeholders is important but relatively difficult as many choose not to comply with information collection efforts. Using stakeholder input provides the focused effort necessary to move on to the additional stages of development of prototype systems for experimentation. Stakeholder requirements will be gathered from each participating transportation affiliate organization for this research. After collecting the stakeholder requirements, a HOQ analysis will be performed for each of the individual stakeholders in the research. From each analysis, a ranking of technical requirements will be determined. After all HOQ studies have been completed the rankings will be tallied and an overall composite technical requirement ranking assigned.

Stakeholder requirements were gathered at a research kick off session held in downtown Lincoln NE in June 2008. Stakeholder meetings that were held were as follows:

- Nebraska State Patrol and Federal Motor Carrier Safety Administration (March 3, 2009)
- Nebraska Department of Motor Vehicles (March 5, 2009)
- Nebraska Department of Roads (March 6, 2009)
- Weigh Station Meeting (April 23, 2009)
  - Nebraska State Patrol (April 23, 2009)
  - Nebraska Department of Roads (April 23, 2009)
- Warner Trucking (CVO) (August 11, 2009)

The stakeholders described in this research include Nebraska Carrier Enforcement Division (CED), Nebraska license plate manufacturer Cornhusker State Industries and 3M, the Department of Motor Vehicles, the Nebraska Department of Roads (NDOR) Intelligent Transportation Division, NDOR Transportation Planning Division, and the Nebraska State Patrol. Based on the verbal information gathered from the initial meeting several requirements were agreed to. The Carrier Enforcement group wanted better PrePass Data Capture and design for use with current databases was their top requirement. The stakeholder requirements for Cornhusker State Industries (CSI) included: Embedding RFID chips inside license plates that won't interfere with RFID scans, ensuring that the RFID tags inside license plates work, designing a RFID license plate manufacturing process, and producing RFID tags at an affordable price. The stakeholder requirements for the Department of Motor Vehicles (DMV) included: ability to tie Performance

Registration Information Systems Management (PRISM) data to the readers, and The Motor Carrier Division wanted the Commercial Vehicle Information Exchange Window (CVIEW) application to tie in to RFID, and capturing mileage traveled using RFID. The stakeholder requirements for the Nebraska Department of Roads-Intelligent Transportations Systems included integrating ITS, networking all readers together, and adaptability to current databases. The stakeholder requirements for the Nebraska Department of Roads-Planning were focused around using readers for data collection and traffic counting. The stakeholder requirements for the Nebraska State Patrol (NSP) included the tracking of non-compliant CVO license plates and the ability to use current NSP databases. The CVOs viewed the RFID license tag more as a regulations challenge than beneficial to their needs, and didn't have any customer requirements for the RFID system other than costs.

5.2 HOQ Construction

The individual QFD house of quality was built by placing the customer requirements for the stakeholder on the left hand side of the chart and then the design elements, which are transponder read distance, physical limitation, read rate, display relevant information, RFID tag number, manufacturing cost are placed on the top of the chart. Once the requirements are entered a diagram can be used to demonstrate the relationships between the customer needs and technical design elements. The standard practice is to symbols to relate to the strength of the association between the design elements and the customer requirements. Each level of interrelationship weighting is assigned a score. The associations are assigned a score of 1, 3, or 9 (Foster), where 9 means strongly associated, 3 is somewhat associated and 1 is weakly associated as shown in Figure 9.

Customers Requirements / Technical Requirements	RFID tag (Transponder) Read Distnace	Physical Limitation	Read Rate	Display Relevant Information	RFID tag number	Manufacturing Cost
Data Capture	●	●	○	●	●	Δ
Design for Non-weigh station Prepass Usage	Δ	●	○	○	○	○
Better performance than other Transponder Systems	●	○	○	●	○	
Simplify Audit Process	●	●	●	●	●	
Increased Audit Area using Roadside Readers				●	●	●
Improve Safety Process				●	●	○
Ability to Use of Current Databases	Δ	Δ	Δ	●	●	Δ

Symbols
● = 9 (Strong association)
○ = 3 (Somewhat associated)
Δ = 1 (Weak association

Figure 9. Demonstrating the relationships

Normally the next step would be performed to assess how a product compares with those of its key competitors by using a five-point scale with five being high and one being low.

Two assessments are done, one for customer requirements and another for technical requirements. This step could apply to comparing other technologies to RFID or comparing one RFID technology to another. Next the customer requirements are prioritized. The priorities including importance to customer, project critical, mission critical and absolute weight on the far right side of the HOQ. Importance is on a 10-point scale, with 10 being most important, and this represents how important the requirement is to the customer. Mission critical values are set on a 5-point scale where 1 is no change, 3 mean the requirement is an improvement on the current process, and 5 is make the process better than the current technology. The project critical value is established on a scale of 1 or 2, with 2 meaning high value and 1 being low value. The project values are judged based on the value to the current operating philosophy, where as the mission critical items relate to future capabilities.

Next the absolute weight is found by multiplying importance values, mission critical values and project critical values (Figure 10).

					Importance	Mission Critical	Project Critical	Absolute weight
					10	5	2	100
					5	3	2	30
					5	3	1	15
					5	1	1	5
					1	3	2	6
					5	3	1	15
					10	5	2	100

Figure 10. Prioritizing Customer Requirements

Once the absolute weight for the customer requirements is calculated the technical requirements need to be prioritized. The priorities include target value, absolute weight, and relative weight. The target value is defined the same way the target values for the customer requirements are calculated by ranking them in order of importance. The value for absolute weight is the sum of the products of relationships between customer and technical requirements and the importance to the customer columns. The value for relative weight is the product of the column of relationships between customer and technical requirements and customer requirements absolute weights (Figure 11).

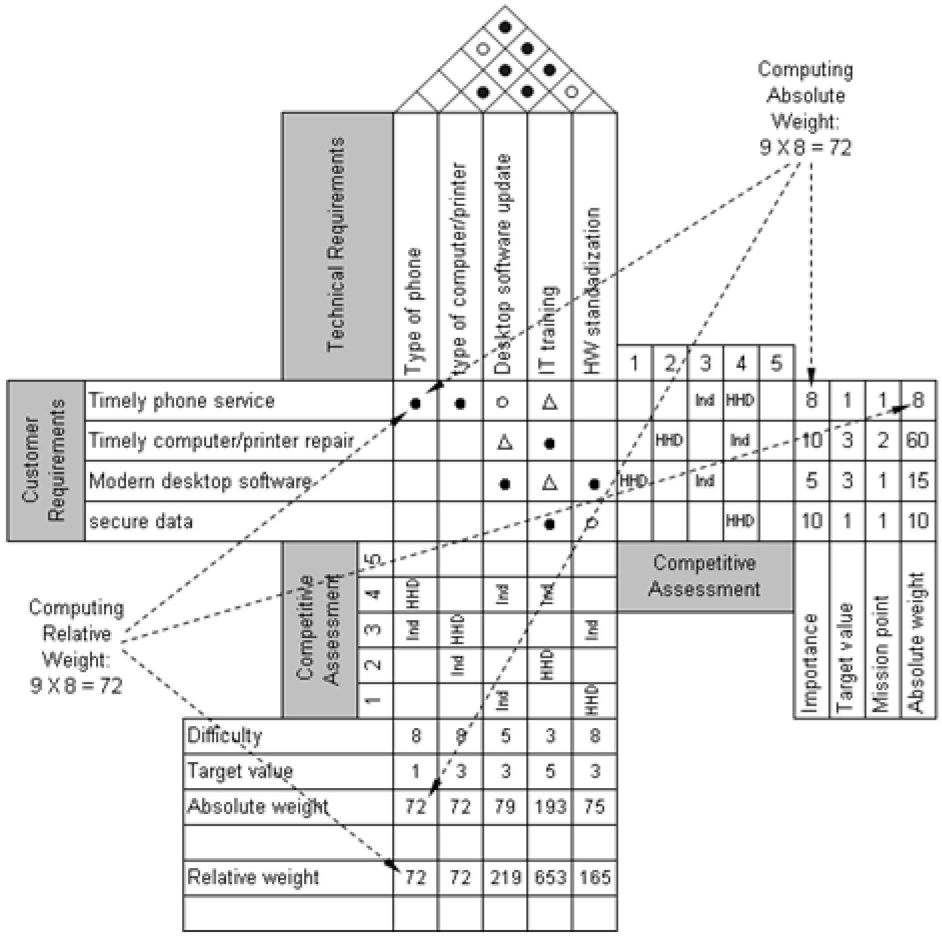

Figure 11. Example of how to calculate weights

5.3 HOQ Analysis

The HOQ was analyzed in two ways 1) analysis of customer requirements, and 2) analysis of technical requirements. First the individual stakeholders HOQs were completed and then the full overall analysis was done.

5.3.1 Analysis of Customer Requirements

In the quality function deployment, the main factors will be the technical requirements; there are also many customer requirements that associate to each technical requirement. The initial twenty eight customer requirements identified by each stakeholder were:

- Data capture- the ability to scan the tag
- Ensure embedded RFID chip inside license plate works
- Tracking of individuals, especially non-compliant CVO license plates
- Design for non-weigh station PrePass usage- wanted a design that could fit roadside usage
- Design working RFID license plate manufacturing process
- Better performance than other transponder systems
- Simplify audit process- wanted to have data on the tags that could display last audit info
- Increased audit area using roadside readers
- Improve safety process- wanted the tag data to display safety violations
- Ability to use of current databases- wanted the RFID system to be interoperable
- Work with suppliers- wanted to work directly with RFID suppliers to purchase and maintain hardware
- Production cost- wanted to keep cost of making the license plate inexpensive
- PRISM- wanted to tie into current database
- CVIEW- wanted the system to work with current database

- Increased mileage traveled using readers- the tag read location could be queried in a database to give miles traveled
- Integrating the important current system in RFID System
- Placing more sensors in specific areas- wanted to use a roadside
- Network all readers together- might assist with tracking efforts
- Traffic counting- wanted the use the number of reads for planning purposes
- Use RFID in the place of present radar
- Enhance road operations (maintenance)
- Range of reader wanted to know the distance the RFIS system could transmit reads
- Speed enforcement- wanted to use the system to detect speed
- Mobile vehicle data collection- wanted a system that was mobile
- Access control- wanted a system that could restrict info to certain users
- Used for mobile proximity sensors
- Power the RFID tag by vehicle battery
- Relate RFID tag with license ID and information.

5.3.2 Analysis of Technical Requirements

The technical requirements were based on the RFID system that was used for the initial test-bed setup. A passive RFID system was chosen because of the low procurement cost ($2500 per reader) and the added specification that the passive tags used for the study cost around thirty cents depending on the amount purchased in bulk. After collecting the stakeholder requirements, a HOQ analysis was performed for each of the individual stakeholders in the research. From each analysis, a ranking of technical requirements was developed. After all HOQ studies had been completed the rankings were tallied and an overall composite technical requirement ranking was assigned. Table 5 illustrates the individual stakeholder rankings.

Table 5. Individual Stakeholder Ranking

	Individual Stakeholder Rankings						Total
Technical Requirements	CED	CSI	DMV	NDOR-ITS	NDOR-Planning	NSP	
RFID tag Reader Distance	4	4	5	5	1	2	21
Physical Limitation	5	1	3	5	1	5	20
Read Rate	3	5	5	3	5	4	25
Display relevant information	2	1	1	2	3	3	12
RFID Tag Number	1	6	1	1	3	1	13
Manufacturing Cost	6	1	3	3	6	6	25

The ability to display relevant information is the overall top technical requirement for implementing an RFID License Plate System. Relevant information will include items that the stakeholders will deem necessary if the RFID system is implemented. The second most important technical requirement is the RFID Tag Number. These technical requirements were followed by physical limitations; RFID tag (transponder) read distance, read rate, and manufacturing costs. The manufacturing costs for the passive system was determined to be a negligible requirement due to a 3M license plate process that could be used by CSI using the current manufacturing setup.

5.3.3 Customer Requirements

The absolute weight of customer requirements is shown for each stakeholder analysis in Appendix B of this document. The HOQ charts are also shown respectively for every Nebraska transportation stakeholder that participated in this study.

All of the individual HOQ's yielded the following important objectives for the stakeholders.

5.3.3.1 CED Results

The Carrier Enforcement Division customer requirements listed in the order of most important to least were:

- data capture
- design for non-weigh station PrePass usage
- better performance than other transponder systems
- simplify audit process
- increased audit area using roadside readers

- improve safety process
- ability to use current databases

The analysis showed that data capture and the ability to use current databases were the two most important requirements, with increased audit area using roadside readers and simplifies audit process being the least important.

5.3.3.2 CSI Results

The RFID license plate requirements for Cornhusker State Industries listed in their preferred order of importance are:

- ensure embedded RFID chip inside license plate works
- work with suppliers
- design working RFID license plate manufacturing process
- production cost

The HOQ yields that the requirement embedded RFID chip in works inside the license plate is in fact the number one preferred requirement but the second ranked preference is to design a working RFID license plate manufacturing, while working with suppliers was third.

5.3.3.3 DMV Results

The Nebraska Department of Motor Vehicles requirements were straightforward. Out of the five main requirements three were related to using current databases. Their rankings were:

- PRISM
- CVIEW
- increased mileage traveled using readers
- integrating the important current system in RFID system
- improve safety process

Four out of the five requirements all scored the same weight making their top choices; PRISM, integrating the current system, CVIEW and increased mileage traveled using readers. This ranking might introduce some bias into the full stakeholder analysis due to almost all of the requirements having such a high score.

5.3.3.4 NDOR-ITS Results

The Nebraska Department of Roads Planning Intelligent Transportation Systems Division five requirements were mirrored in some of the other stakeholder's requirements their preferences in order were:

- integrating the important current system in RFID system
- placing more sensors in specific areas
- network all readers together
- ability to use current databases
- production cost

Integrating current system and networking all readers together, also having the ability to adapt to current databases were the top three weights of one hundred, while production costs and placing more sensors in specific areas scored very low.

5.3.3.5 NDOR-Planning Results

The Nebraska Department of Roads Planning Division requested four requirements that are again list in order of preference:

- traffic counting
- use RFID in the place of present radar
- enhance road operations (maintenance)
- range of reader

NDOR Planning only had one top requirement which was to use the RFID readers for data collection for traffic counting. The other three requirements scored very low.

5.3.3.6 NSP Results

The Nebraska State Patrol had very different ideas for the RFID system their requirements were:

- tracking of individuals, especially non-compliant CVO license plates
- range of reader
- speed enforcement
- mobile vehicle data collection
- access control

- ability to use current databases

Once the analysis was done the out of scope requirements fell out of the ranking due to their low scores. The top scoring requirements are tracking of non-compliant Commercial Vehicle Operator (CVO) license plates and the ability to use current NSP databases.

In this next part of the results the analysis shows the most important technical requirements based on the customer inputs.

5.3.4 Technical Requirements

Results for the technical requirements from the HOQ are shown in Table 4, where Absolute Factor (AF) and Relative Factor (RF) were used to determine the most significant technical factors for these stakeholders.

Table 6. Final Evaluation from HOQ

	CED		CSI		DMV		NDOR-ITS		NDOR-P		NSP	
	AF	RF	AF	RF	AF	RF	AF	RF	AF	RF	AF	RF
RFID tag (Transponder) Read Distance	0.16	0.15	0.23	0.20	0.03	0.03	0.09	0.04	0.21	0.23	0.22	0.20
Physical Limitation	0.17	0.17	0.23	0.20	0.09	0.09	0.09	0.04	0.21	0.23	0.16	0.12
Read Rate	0.09	0.07	0.12	0.10	0.03	0.03	0.07	0.07	0.11	0.09	0.17	0.19
Display Relevant Information	0.28	0.28	0.23	0.20	0.39	0.38	0.33	0.35	0.22	0.22	0.15	0.18
RFID tag number	0.25	0.27	0.10	0.07	0.39	0.38	0.37	0.43	0.22	0.22	0.28	0.26
Manufacturing Cost	0.05	0.05	0.09	0.24	0.07	0.10	0.06	0.05	0.02	0.02	0.02	0.04

From Table 6, the most significant technical factor for CED is RFID tag numbers; the most significant factors for CSI include: Physical Limitation, Display Relevant Information and Manufacturing Cost. For DMV include: Display Relevant Information and RFID tag numbers, for NDOR-ITS is RFID tag number, for NDOR-Planning include RFID tag (Transponder) Read Distance and Physical Limitation, and for NSP is RFID tag number. Therefore, the improvement to the factor of RFID tag number is most important to influence the customers' satisfaction. This table also shows that the requirements from DMV and NDOR-ITS are more specific than the others. The significant factors for both include: Display Relevant Information and RFID tag number. For the other four departments, their six technical requirements are almost equivalent.

5.3.5 Full Stakeholder analysis

The full stakeholder analysis was optimized so that close attention was given toward including at least one customer requirement from each stakeholder group. The weights and ranking from each individual analysis was carried over to the full study as not to bias the overall ranking in any particular direction. This yielded the most important requirements for the customers and the particular problems that must be addressed to improve the current system product.

From the HOQ analysis referenced in Figure 12, it is evident to see what the most important objectives for these stakeholders.

- Data capture
- Ensure embedded RFID chip inside license plate works
- Tracking of individuals, especially non-compliant CVO license plates
- Design working RFID license plate manufacturing process
- Ability to use of current database
- Motor Carrier Division
- Use with CVIEW database
- Increased mileage traveled using readers
- Integrating the important current system in RFID system
- Network all readers together
- Traffic counting
- Relate RFID tag with license ID and information

Customers Requirements \ Technical Requirements	RFID tag (Transponder) Read Distance	Physical Limitation	Read Rate	Display Relevant Information	RFID tag number	Manufacturing Cost	Importance	Mission Critcal	Project Critical	Absolute weight
Data Capture	●	●	○	●	●	Δ	10	5	2	100
Ensure embedded RFID chip inside License plate works	●	●	○	●	○	Δ	10	5	2	100
Tracking of Individuals, especially non-compliant CVO license plates	●	○	●	○	○	Δ	10	5	2	100
Design for Non-weigh station Prepass Usage	Δ	●	○	○	○	○	5	3	2	30
Design working RFID License plate manufacturing process	○	○	○	○	Δ	●	10	5	2	100
Better performance than other Transponder Systems	●	○	○	●	○		5	3	1	15
Simplify Audit Process	●	●	●	●	●		5	1	1	5
Increased Audit Area using Roadside Readers				●	●	●	1	3	2	6
Improve Safety Process				●	●	○	5	3	1	15
Ability to Use of Current Databases	Δ	Δ	Δ	●	●	Δ	10	5	2	100
Work with Suppliers	Δ	Δ	Δ	Δ	Δ	●	5	5	2	50
Production Cost	○	○	Δ	○	○	●	5	3	1	15
PRISM				●	●	○	10	5	2	100
CVIEW				●	●	○	10	5	2	100
Increased Mileage Traveled using Readers	○	●	○	●	●	○	10	5	2	100
Integrating the Important Current System in RFID System				●	●		10	5	2	100
Placing more sensors in specific areas	●	●	○	●	○	Δ	5	3	1	15
Network all readers together			○	○	●	Δ	10	5	2	100
Traffic Counting	●	●	○	●	●	Δ	10	5	2	100
Use RFID in the Place of present radar	○	○	○	●	●	Δ	5	1	1	5
Enhance road operations (maintenance)				Δ		Δ	1	1	1	1
Range of reader	●	●	●	Δ	Δ		3	3	1	9
Speed Enforcement	○	○	●	Δ	●	Δ	5	3	2	30
Mobile Vehicle Data Collection	●	●	Δ	○	●	Δ	10	3	1	30
Access Control	Δ	Δ	Δ		●	Δ	5	3	1	15
Used for Mobile Proximity Sensors	●	●	○	●	Δ	Δ	5	5	2	50
Power the RFID Tag by Vehicle Battery		●				○	1	1	1	1
Relate RFID Tag with License ID and Information				●			10	5	2	100

	RFID tag (Transponder) Read Distance	Physical Limitation	Read Rate	Display Relevant Information	RFID tag number	Manufacturing Cost
Target value	1	3	3	5	5	
Absolute weight	804	814	534	1451	1515	279
Absolute factor	0.15	0.15	0.10	0.27	0.28	0.05
Relative weight	5537	5687	3797	11853	12027	3650
Relative factor	0.13	0.13	0.09	0.28	0.28	0.09

Symbols
● = 9 (Strong association)
○ = 3 (Somewhat associated)
Δ = 1 (Weak association

Figure 12. HOQ for all stakeholders

The relative weight of the technical requirements is shown below in Table 7 for all stakeholders together. The relative weights are calculated using the absolute weight of the customer requirements and the assigned value from the association between the customer requirements and the technical requirements. The higher the value of the relative weight the more important the requirement.

Table 7. Final Weights from HOQ

Weight	RFID tag	Physical	Read	Display	RFID	Manufacturing
Absolute	804	814	534	1451	1515	279
Factor	0.15	0.15	0.10	0.27	0.28	0.05
Relative	5537	5687	3797	11853	12027	3650
Factor	0.13	0.13	0.09	0.28	0.28	0.09

Table 7 illustrates that displaying relevant information and RFID tag number are the most important technical requirements for a RFID system. Results for the technical requirements from the HOQ are shown in Table 8. This table shows that the top two significant technical factors for these stakeholders are displaying relevant information and the RFID tag number.

Table 8. Overall Composite Technical Requirement Rankings

Technical Requirements	Ranking
Display Relevant Information	1
RFID Tag Number	2
Physical Limitation	3
RFID tag Read Distance	4
Read Rate	5
Manufacturing Cost	5

5.4 Summary

From the overall total comparison it appears that the NE stakeholders place more importance on the technical requirements of displaying relevant information and RFID tag number. This holds true to the initial rankings. Using the HOQ method the 12 most important objectives were obtained for the stakeholders. Those requirements were: Data capture, ensure embedded RFID chip inside license plate works, tracking of individuals, especially non-compliant CVO license plates, design working RFID license plate manufacturing process, ability to use current database, PRISM, CVIEW, increased mileage traveled using readers, integrating the important current system in RFID system, network all readers together, traffic counting, relate RFID tag with license ID and information. At least one or two of the requirements represent one of each of the individual stakeholder's interests. So it is shown that the many stakeholder requirements can be paired down to a manageable amount allowing a more focused decision to be made. These customer requirements will be used later on for the AHP study

CHAPTER 6 RESEARCH OBJECTIVE #2

By using the DFSS-R Methodology I investigated the second objective and completed the PERFORM portion of the methodology by utilizing the AHP Evaluation.

6.1 Analytic Hierchy Process (AHP) Evaluation

There are five fundamental steps in AHP: Constructing the hierarchy, making pairwise comparisons, determining relative weight calculations, aggregating the relative weights, and verifying consistency in the comparisons (Shapira & Goldenberg). Step one in AHP consists of decomposing a complex problem into a heuristic map that clearly shows the scope of the problem. Heuristics methods such as AHP are appealing due to their ability to quickly evaluate difficult problems by producing near-optimal solutions (Dyer et al.). Heuristics can be used to simplify the problem by generating levels of attributes and alternatives. The three major attributes selected for this situation are reliability, networking, and interoperability.

The second step in the AHP evaluation is to make pairwise comparisons between both the attributes and the alternatives. This is an import step in the decision making process because it represents a set of preferences in a systematic numerical format (Bouyssou, et al). This is done by making comparisons on a pairwise basis, where each pair of entities is evaluated based upon the decision maker’s intuitive judgment and preferences.

The preference and indifference relations on the set A are defined by:

$$\forall a,b \in A, \left\{ \frac{aPb \Leftrightarrow x(a) > x(b)}{aIb \Leftrightarrow x(a) = x(b)} \right\}$$

where *aPb* means "*a* is preferred to *b*" and *aIb* means the decision maker is indifferent between *a* and *b* (Bouyssou et al.). Comparisons are made for each pair of alternatives and transferred to a matrix as shown below in Figure 13. The value P_{ij} is the preference of alternative *i* to alternative *j* and P_{ij}^{-1} is the inverse of that value. The variable *I* means the decision maker is indifferent between those two alternatives.

	a	b	c	d	e
a	I	P_{ab}	P_{ac}	P_{ad}	P_{ae}
b	P_{ab}^{-1}	I	P_{bc}	P_{bd}	P_{be}
c	P_{ac}^{-1}	P_{bc}^{-1}	I	P_{cd}	P_{ce}
d	P_{ad}^{-1}	P_{bd}^{-1}	P_{cd}^{-1}	I	P_{de}
e	P_{ae}^{-1}	P_{be}^{-1}	P_{ce}^{-1}	P_{de}^{-1}	I

Figure 13. Preference structure for a five entity comparison.

Step three consists of calculating the relative weight for each set of attributes throughout every level of the hierarchy. The weight w_i is given by the equation:

$$w_i = \frac{1}{n} \sum_{j=1}^{n} \frac{a_{ij}}{\sum_{k=1}^{n} a_{kj}}$$

where a_{ij} is the element in row *i* and column *j* of the decision matrix. The fourth step is to aggregate the relative weights of each attribute to the overall preferences that were determined so an overall conclusion can be made from the comparisons. The final step in the decision making process is to verify the consistency of the comparisons. Too many pairwise comparisons can become time consuming, which leads to fatigue that may result in increasingly inconsistent decisions (Polatidis et al.). Making consistent decisions is an important aspect in the overall selection of an alternative. However, the original comparison does not need to be perfectly consistent and the entries need not even be transitive (Saaty & Vargas). Instead, only a measure of the error due to inconsistency in the decision making process is needed. This measure is determined by calculating the consistency of the preferences and comparing it to a random index. The consistency index (C.I.) is formed from a comparison matrix by the following equation:

$$C.I. = \frac{\lambda_{\max} - n}{n-1}.$$

The C.I. is then divided by an average random consistency index (R.I.). This index is shown in Table 9, where N is the number of alternatives in the hierarchy.

Table 9. Average random consistency index (R.I.)

N	1	2	3	4	5	6	7	8	9	10
Random Consistency Index (R.I.)	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

Dividing the consistency index by the random consistency index provides the consistency ratio (C.R.), which is a measure of the decision maker's consistency between choices in the preference matrix. The consistency ratio equation is shown below.

$$C.R. = \frac{C.I.}{R.I.}$$

According to Saaty and Vargas a consistency ratio of 10 percent or less implies that the adjustment is small compared to the actual values of the eigenvector entries and therefore, the decision maker's preferences are acceptable.

6.2 AHP Setup

The three major attributes that should be utilized with AHP as a tool for selecting one RFID system versus another should be reliability, networking, and interoperability. Reliability may consist of reducing set up time or throughput time to scan a tag, and can focus on either the distance required to read a tag or the maximum speed of progression that will limit the tag scans. Networking would address the ability to receive and transmit data over the entire statewide/regional system, while interoperability involves the ease of implementation with the various stakeholder's current databases and data collection systems, which would reduce the down time required to install a new system and the learning curve for training employees. These three characteristics, or attributes, can be considered as benefits, while the economic considerations can be deemed either a benefit or cost. The focus of this research was to use the stakeholder/ customer requirements as criteria for arriving at which alternative the Nebraska stakeholders judged to be most important. The framework of this decision model can then be used assist decision making for future Nebraska projects.

Using the HOQ method obtained the most important objectives for the stakeholders:

- Data capture
- Ensure embedded RFID chip inside license plate works
- Tracking of individuals, especially non-compliant CVO license plates
- Design working RFID license plate manufacturing process
- Ability to use current database
- Motor Carrier Division
- CVIEW
- Increased mileage traveled using readers
- Integrating the important current system in RFID system
- Network all readers together
- Traffic counting
- Relate RFID tag with license ID and information

For ease of analysis all of the customer requirements can be categorized or classified into three main groups (see Figure 14). The groups are Networking, Reliability, and Interoperability.

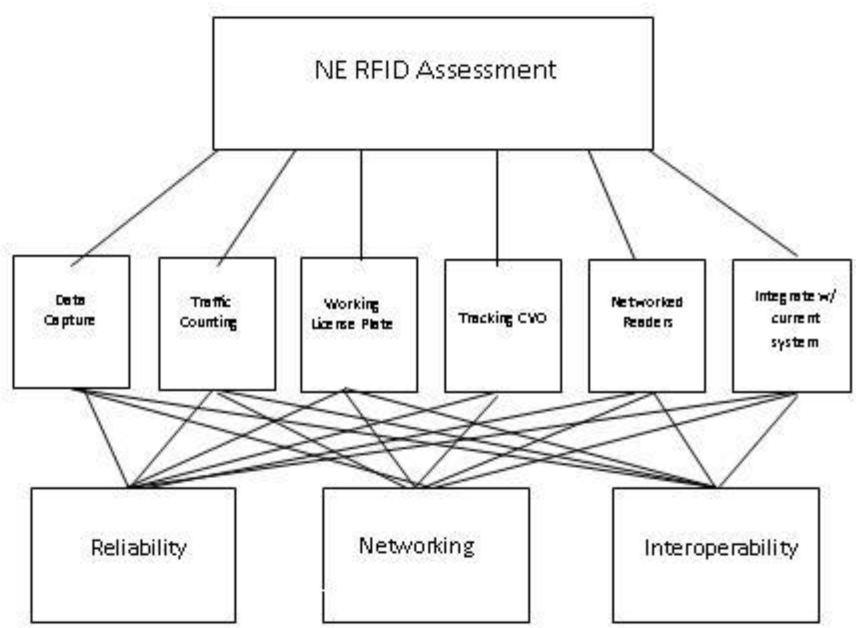

Figure 14. Categorized customer requirements

The networking category is comprised of the customer requirements:

- Network all readers together
- Increased mileage traveled using readers
- Tracking of individuals, especially non-compliant CVO license plates

The increased mileage and tracking requirements can only be achieved if there is a networked system. The reliability group is comprised of:

- Data capture

- Traffic counting
- Working license plate

The data capture, traffic counting, and working plate are functions of the system being reliable. While the last group interoperability, is solely comprised based on the system being able to integrate with the current infrastructure and costumer databases. The interoperable group is made up of the following requirements:

- CVIEW
- Use current databases
- Relate RFID tag with license ID and information
- Integrating the important current system in RFID system
- PRISM

The customer requirements: PRISM, CVIEW, integrating the important current system in RFID system, ability to use current database, and relate RFID tag with license ID and information, can all be combined as part of a single requirement entitled interoperable. All of these requirements focus on the customer wanting the RFID system to operate using their current databases/ infrastructure. The increased miles and tracking non-compliant CVO requirements were combined into one requirement entitled tracking of CVO. This narrows the focus to six main requirements:

- Interoperability
- Data capture
- Traffic counting

- Working plate
- Networking
- Tracking CVO

These requirements were then discussed with the stakeholders as pairwise comparisons to rank in terms of importance. Using the following scale in Table 10:

Table 10. Pairwise comparison scale

Intensity of Importance	**Definition**	**Explanation**
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one activity over another
5	Strong importance	Experience and judgment strongly favor one activity over another
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values	

Using the definitions for the comparisons transportation customers then gave their preferences for their attributes that were based on their customer requirements. Figure 15 and 16 show example rankings of the six RFID attributes.

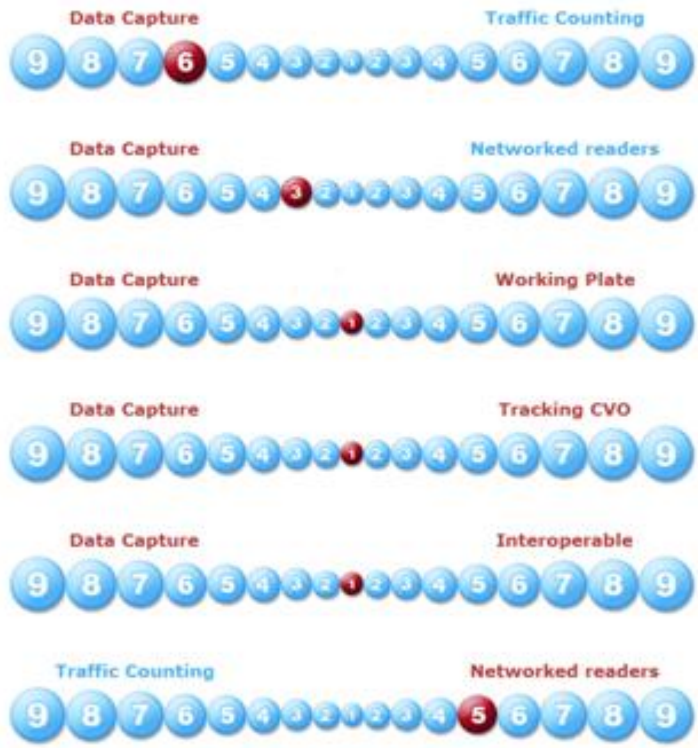

Figure 15. Example of Stakeholder preferences

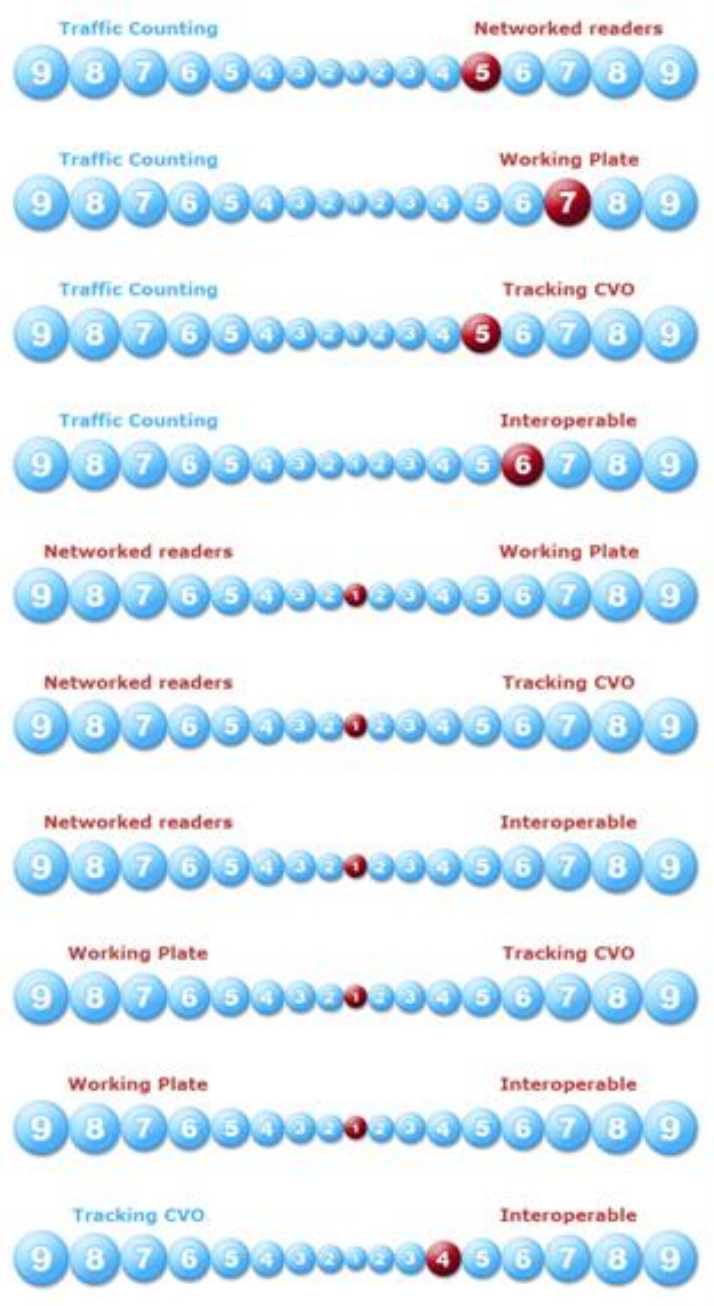

Figure 16. Example of Stakeholder preferences

6.3 AHP Analysis

In order to perform the analysis the number rankings from the pairwise comparisons are entered into a six by six matrix since there are six attributes to compare. The values are entered corresponding to the following rules:

1. If the judgment value is on the left side of 1, put the actual judgment value in the matrix.
2. If the judgment value is on the right side of 1, put the reciprocal value in the matrix.

Next Sum each column of the reciprocal matrix and then each element of the matrix is divided by the sum of its column, this yields the normalized relative weight. The sum of each column is 1. The normalized principal Eigen vector can be obtained by averaging across the rows. The normalized principal Eigen vector is also called priority vector. Since it is normalized, the sum of all elements in priority vector is 1. The priority vector shows relative weights among the things that are compared. The relative weight is a ratio scale that can be divided among the elements. This gives descriptive ratios for the preferences. Aside from the relative weight, the consistency of the preferences must be checked. The consistency value lends credibility to whether or not the comparisons were valid. To do this the Principal Eigen value (λ_{max}) is needed. The Principal Eigen value is obtained from the summation of products between each element of Eigen vector and the sum of columns of the matrix.

6.3.1 NDOR Analysis

The stakeholder pairwise rankings (Table 11) were complied into a matrix format and then the Eigen values and vectors were computed to yield the preferences.

Table 11. NDOR Rankings

NDOR	Data Capture	Traffic Counting	Networked Readers	Working Plate	Tracking CVO	Interoperable
Data Capture	1	1/2	1	5	6	3
Traffic Counting	1	1	3	1/4	5	8
Networked Readers	1	1/3	1	6	7	6
Working Plate	1/5	4	1/6	1	6	4
Tracking CVO	1/6	1/5	1/7	1/6	1	1/5
Interoperable	1/3	1/8	1/6	1/4	5	1

The indicator to show consistency of the AHP is:

$$CI = \frac{\lambda - n}{n-1}$$

where λ is the maximum characteristic root of the matrix A.

When the ratio CR=CI/RI<0.1, it passes the consistency test, otherwise it fails which means it is not powerful enough.

In this case, the maximum characteristic root of A is 8.522 and RI of n=6 is 1.24. The confidence ratio is:

$$CR=\frac{CI}{RI}=\frac{\frac{8.522-6}{6-1}}{1.24}=0.4069$$

The findings are inconsistent for the NDOR rankings because CR>0.1. It is interesting to note that the NDOR rankings indicate that the Priority vector yields:

$$W=\begin{matrix}0.201073\\0.280417\\0.237798\\0.19694\\0.024921\\0.058851\end{matrix}$$

The vector provides the relative weights are data capture 20%, traffic counting 28%, networked readers 24%, working plate 20%, tracking CVO 2%, and interoperable is 6%.

This means that the NDOR stakeholder prefers the alternative traffic counting 1.39 times more than data capture, 1.18 times more than networking of readers, 1.42 times more than a working plate, and 11.25 times more than tracking CVO, and 4.76 times more than interoperability.

6.3.2 CSI Analysis

Following the same format as the NDOR ranking the CSI stakeholder pairwise rankings (Table 12) were complied into a matrix format and then the Eigen values and vectors were computed to yield the preferences.

Table 12. CSI rankings

CSI	Data Capture	Traffic Counting	Networked Readers	Working Plate	Tracking CVO	Interoperable
Data Capture	1	1	1	1	5	5
Traffic Counting	1	1	1/5	1/5	5	5
Networked Readers	1	5	1	1	5	5
Working Plate	1	5	1	1	5	5
Tracking CVO	1/5	1/5	1/5	1/5	1	3
Interoperable	1/5	1/5	1/5	1/5	1/3	1

In this case, the maximum characteristic root of A is 6.838 and RI of n=6 is 1.24. The ratio

$$CR = \frac{CI}{RI} = \frac{\frac{6.838-6}{6-1}}{1.24} = 0.1352$$

The findings are considered inconsistent due to the confidence ratio, but they are very close to the threshold for the CSI rankings because CR>0.1. The CSI rankings indicate that the Priority vector yields:

$$W = \begin{matrix} 0.217697 \\ 0.143623 \\ 0.27146 \\ 0.27146 \\ 0.057428 \\ 0.038331 \end{matrix}$$

This vector shows the relative weights are data capture 22%, traffic counting 14%, networked readers 27%, working plate 27%, tracking CVO 6%, and interoperable is 4%. This means that the CSI stakeholder prefers the alternatives networked reader and working plate 1.25 times more than data capture, 1.89 times more than traffic counting, 4.73 times more than tracking CVO, and 7.08 times more than interoperability.

6.3.3 CED Analysis

Using the CED stakeholder pairwise rankings (Table 13), the AHP analysis was conducted. The customer feedback was complied into a matrix format and then the Eigen values and vectors were computed to yield the preferences.

Table 13. CED rankings

CED	Data Capture	Traffic Counting	Networked Readers	Working Plate	Tracking CVO	Interoperable
Data Capture	1	6	3	4	5	2
Traffic Counting	1/6	1	1/3	1/2	1	1/4
Networked Readers	1/3	3	1	3	2	1/2
Working Plate	1/5	2	1/3	1	2	1/3
Tracking CVO	1/4	1	1/2	1/2	1	1/2
Interoperable	1/2	4	2	3	2	1

In this case, the maximum characteristic root of A is 6.216 and RI of n=6 is 1.24. The confidence ratio is:

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} = \frac{\frac{6.216 - 6}{6 - 1}}{1.24} = 0.0348$$

The findings are consistent for the CED rankings and the Priority vector yields:

$$W = \begin{matrix} 0.389004 \\ 0.05775 \\ 0.160833 \\ 0.092616 \\ 0.076385 \\ 0.223412 \end{matrix}$$

giving the relative weights of 40% for data capture, 6% for traffic counting, 16% for networked readers, 9% for working plate, 8% for tracking CVO, and 22% for interoperable. This means that the CED stakeholder prefers the alternative data capture 6.74 times more than traffic counting, 2.42 times more than networking of readers, 4.2 times more than a working plate, and 5.09 times more than tracking CVO, and 1.74 times more than interoperability.

6.3.4 NSP Analysis

The NSP stakeholder pairwise rankings were condensed into Table 14. The customer feedback was complied into a matrix format and then the Eigen values and vectors were computed to yield the preferences.

Table 14. NSP rankings

NSP	Data Capture	Traffic Counting	Networked Readers	Working Plate	Tracking CVO	Interoperable
Data Capture	1	8	1/2	1	1/6	2
Traffic Counting	1/8	1	1/7	1	1/8	1/7
Networked Readers	2	7	1	1	1/5	1
Working Plate	1	1	1	1	1/7	1/6
Tracking CVO	6	8	5	7	1	2
Interoperable	1/2	7	1	6	1/2	1

In this case, the maximum characteristic root of A is 7.002 and RI of n= 6 is 1.24. The confidence ratio is:

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} = \frac{\frac{7.002 - 6}{6 - 1}}{1.24} = 0.1616$$

The confidence ratio is close to the consistent threshold for the NSP rankings and the Priority vector yields:

$$W = \begin{matrix} 0.142642 \\ 0.033262 \\ 0.13895 \\ 0.065539 \\ 0.431742 \\ 0.187865 \end{matrix}$$

giving the relative weights of 14% for data capture, 3% for traffic counting, 14% for networked readers, 7% for working plate, 43% for tracking CVO, and 19% for interoperable. This means that the NSP stakeholder prefers the alternative tracking CVO 3.03 times more than data capture, 12.98 times more than traffic counting, 3.11 times more than networking of readers, 6.59 times more than working plate, and 2.3 times more than interoperability.

6.3.5 DMV Analysis

The DMV customer feedback (Table 15) was complied into a matrix format and then the Eigen values and vectors were computed to yield the preferences.

Table 15. DMV rankings

DMV	Data Capture	Traffic Counting	Networked Readers	Working Plate	Tracking CVO	Interoperable
Data Capture	1	6	7	1	1	1
Traffic Counting	1/6	1	1	1/7	1/7	1
Networked Readers	1/7	1	1	1/7	1/7	1
Working Plate	1	7	7	1	2	7
Tracking CVO	1	7	7	1/2	1	1
Interoperable	1	1	1	1/7	1	1

For this study the maximum characteristic root of A is 6.636 and RI of n= 6 is 1.24. The confidence ratio is:

$$CR=\frac{CI}{RI}=\frac{\frac{6.636-6}{6-1}}{1.24}=0.1026$$

The confidence ratio is close to the consistent threshold for the DMV rankings so they are considered valid and the Priority vector yields:

$$W = \begin{matrix} 0.233094 \\ 0.04716 \\ 0.046239 \\ 0.355206 \\ 0.211885 \\ 0.106415 \end{matrix}$$

giving the relative weights of 23% for data capture, 5% for traffic counting, 5% for networked readers, 36% for working plate, 21% for tracking CVO, and 11% for interoperable. This means that the DMV stakeholder prefers the alternative working plate 1.52 times more than data capture, 7.53 times more than traffic counting, 7.68 times more than networking of readers, 1.68 times more than tracking CVO, and 3.34 times more than interoperability.

6.3.6 Grouped Analysis

In order to get a single AHP analysis for the RFID alternatives that the State of Nebraska transportation stakeholders identified the data had to be aggregated. For an AHP study the individual rankings are averaged (Table 16) and then complied into a matrix for calculation of the Eigen values and priority vector.

Table 16. Grouped rankings

Group	Data Capture	Traffic Counting	Networked Readers	Working Plate	Tracking CVO	Interoperable
Data Capture	1	5	4	5	4	3
Traffic Counting	1/5	1	1	1/3	3	3
Networked Readers	1/4	1	1	3	3	4
Working Plate	1/5	3	1/3	1	3	3
Tracking CVO	1/4	1/3	1/3	1/3	1	1
Interoperable	1/3	1/3	1/4	1/3	1	1

For the grouping study the maximum characteristic root of the matrix is 6.934 and RI of n= 6 is 1.24. The confidence ratio is:

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} = \frac{\frac{6.934 - 6}{6 - 1}}{1.24} = 0.1506$$

The confidence ratio is considered inconsistent even though the value is close to the consistent threshold for the group rankings; given this the Priority vector yields:

$$
W = \begin{matrix} 0.410795 \\ 0.124907 \\ 0.188132 \\ 0.15286 \\ 0.059434 \\ 0.063872 \end{matrix}
$$

This gives the relative weights of 41% for data capture, 12% for traffic counting, 19% for networked readers, 15% for working plate, 6% for tracking CVO, and 6% for interoperable. This means that the group of transportation stakeholders prefers the alternative data capture 3.29 times more than traffic counting, 2.18 times more than networking of readers, 2.69 times more than a working plate, 6.91 times more than tracking CVO, and 6.43 times more than interoperability.

6.4 Summary and Comparative Analysis

Two important issues in group decision making are: how to aggregate individual judgments in a group into a single representative judgment for the entire group, and how to construct a group choice from individual choices. Judgments must be combined so that the reciprocal of the synthesized judgments is equal to the syntheses of the reciprocals of these judgments (Saaty). It has been proved that the geometric average, and not the arithmetic average, is the only way to do that. If the individuals are experts, they may not wish to combine their judgments but only their final outcomes obtained by each from their own hierarchy. In that case one takes the geometric average of the final outcomes. If the individuals have different priorities of importance, their judgments (final outcomes) are raised to the power of their priorities and then the geometric average is formed. When comparing the priority vector of the group analysis to the average of the individual priority vectors the differences were only minor in two of the alternatives (Table 17).

Table 17. Average priority vectors

	NDOR	CSI	CED	NSP	DMV	AVG	Group
Data Capture	20.11%	21.77%	38.90%	14.26%	23.31%	23.67%	41.08%
Traffic Counting	28.04%	14.36%	5.77%	3.33%	4.72%	11.24%	12.49%
Networked Readers	23.78%	27.15%	16.08%	13.89%	4.62%	17.11%	18.81%
Working Plate	19.69%	27.15%	9.26%	6.55%	35.52%	19.64%	15.29%
Tracking CVO	2.49%	5.74%	7.64%	43.17%	21.19%	16.05%	5.94%
Interoperable	5.89%	3.83%	22.34%	18.79%	10.64%	12.30%	6.39%

Both the average ranking and overall group rankings total to 100% each. Overall if the average rankings should be similar to the group rankings, but the averaged ranking indicate that data capture is preferred 2.11 times more than traffic counting, 1.38 time more than networked readers, 1.21 more than working plate, 1.48 times more than tracking of CVO and 1.92 times more than interoperable. These preferences don’t yield a significant difference overall for the group whereas the group ranking shows more variability. This difference between the two could be caused by some of the high confidence ratios or stem from combining the NDOR stakeholder preferences into one analysis. The large differences might also stem from the NDOR rankings being highly inconsistent while the other ranking were all close to the threshold for inconsistency. The overall conclusion from the analysis is that whether the average or grouped ranking is used data capture is still the most important attribute for a RFID license plate system. This diagnosis shows that AHP can be used a tool to assist the Nebraska transportation stakeholders with selecting preferred RFID system. This tool can also be used for cost benefit analysis of the alternatives if pricing information is provided for the desired systems. The full AHP analysis for all groups can be found in Appendix C.

CHAPTER 7 RESEARCH OBJECTIVE #3

By using the DFSS-R Methodology the third objective was investigated and completed using the PREDICT portion of the methodology by utilizing Design of Experiments.

7.1 Design of Experiments

DOE is a quality analysis tool that is utilized in the analysis, design and identify loop of the DFSS-R methodology. This tool uses information learned from the first or previous experiments to eliminate unnecessary or undesirable experimentation within the previous series of experiments. This method provides a powerful means to achieve breakthrough improvements in product quality and process efficiency (Jones). This research will focus on reliability/readability testing to determine the opportunities and shortcomings of a RFID license plate system and mile marker reader. Reliability is ability for a product or a system to perform consistently. This research utilized quality measurements such as statistical reliability to test the feasibility of our proposed system.

7.2 Equipment and Testing Protocol

The equipment for this experiment included two RFID antennas, a computer, TagDemo software, a Samsys reader, Generation 2 tags (newest RFID protocol tags available), and a stopwatch. From these components, a basic Passive RFID system was constructed. A Passive RFID system has three components. They are a scanning antenna, a transceiver with a decoder to capture the data, and a transponder (RFID) that has been programmed with information. The antenna transmits radio frequency signals and provides a means of communication with the transponder and also provides the RFID tag with energy to communicate. The experiments tested the reading range of the Generation 2 tags at two different antenna and tag heights, the maximum distance for an active RFID license plate read and the optimal location for tag placement for an RFID license plate. All of these experiments were designed to serve as initial/baseline testing of the commercial off the shelf RFID system that was purchased based on the customer and technical requirements from the HOQ and AHP analysis.

Because of the different antenna and tag heights, the experiment will have multiple sections. Each experiment will correspond to a different antenna or tag heights (Figure 18). The equipment to be used for testing the passive technologies met the International Organization for Standardization (ISO) 18000 standard or EPC Global compliant readers and tags. The equipment tested for active technologies will be based upon the ISO 18000 – 7 standards, which give the parameters for the RFID air interface communications.

7.3 Baseline License Plate Tag Location

The initial research testing protocol focused on testing of RFID tags on license plates so that the overall readability or performance could be determined. The sequence of testing included (1) baseline testing of passive tags behind license plates, (2) testing passive tags embedded between license plates, (3) testing of passive tag in front of license, and (4) active tags embedded between license plates (Figure 17).

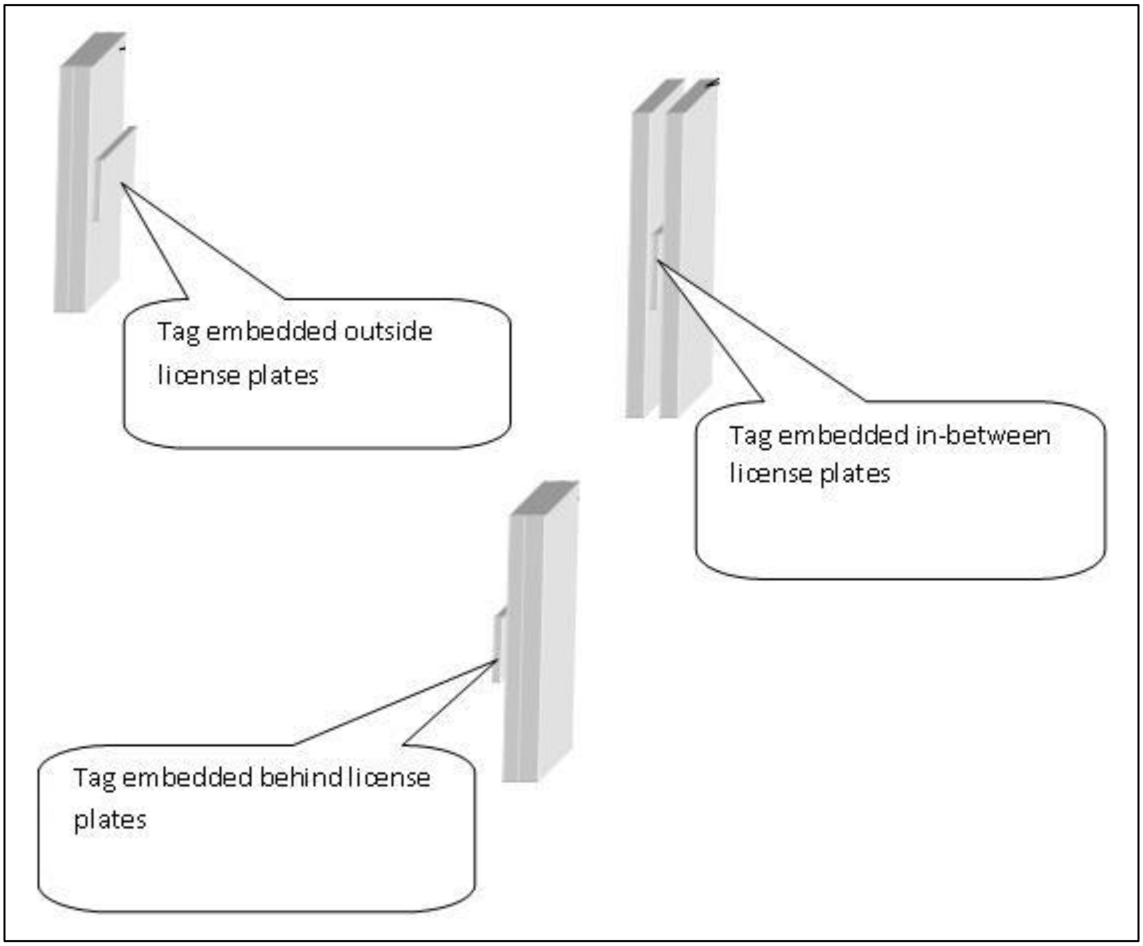

Figure 17. Location of the tag embedded in license plates

This experiment was setup using a full factorial 3^3 design. The dependent variable for this study was received signal strength, and the independent variables were location (inside, outside, in-between), vertical height (1ft, 2ft, 3ft), and horizontal distance (1ft, 5ft, 10ft). Because the three independent variables are comprised of three factors each the DOE is called a full factorial 3^3 design (Montgomery).

The results of the analysis of the baseline passive testing experiment yield that height (vertical), distance (horizontal), and the interaction of height and distance are extremely significant (using an alpha value of $p < 0.05$). The rationale behind this interaction is that the height of the antenna affects the distance of the read. Normally if the interaction between two variables is significant then no conclusions can be drawn from these variables if they are also found to be significant. However, simple comparisons of RSSI means across the three categories of vertical height indicate that all of height levels are statically significant (see vertical pairwise comparisons table in appendix H). Similarly a simple comparison of RSSI means across the tree categories of the horizontal distance indicate that the 1 and 5 foot levels are statistically significant while the 10 foot level was found not to have any effect on the RSSI at a confidence level of 95% (see horizontal pairwise comparisons table in appendix I). The location (the placement of the tag) is not statistically significant. The reason that there is a lack of statistical significance in the location factor is because the cardboard and license plates do not have a significant effect on the transmission and overall broadcasting of radio frequency (RF) signals. The R square value for passive testing in the ANOVA model is 0.613 (Table 18), which is a good value. This means a large proportion of the variation of the actual observations around the mean is being explained by the fitted line.

Table 18. ANOVA for license plate passive tag location

Dependent Variable: RSSI decibels (dB)

Source	Type III Sum of Squares	df	Mean Square	F	P-value
Corrected Model	1.572E7	26	604773.798	22.998	.000
Intercept	8.995E7	1	8.995E7	3420.774	.000
Location	119526.049	2	59763.025	2.273	.104
Vertical	8387650.686	2	4193825.343	159.483	.000
Horizontal	2583125.101	2	1291562.551	49.116	.000
Location * Vertical	174383.432	4	43595.858	1.658	.159
Location * Horizontal	107441.506	4	26860.377	1.021	.396
Vertical * Horizontal	4261870.558	4	1065467.640	40.518	.000
Location * Vertical * Horizontal	90121.412	8	11265.177	.428	.904
Error	9940031.600	378	26296.380		
Total	1.156E8	405			
Corrected Total	2.566E7	404			

a. R Squared = .613 (Adjusted R Squared = .586)

7.4 Passive Tag Read Distance

Due to the variables of different heights, the experiment had four separate parts. Each part corresponded to a different antenna or tag height. These heights for the antennas were 3 feet and 6 feet. Markers on the ground were marked precisely measuring distance in feet. The test ranged from 0 to 20 feet. With two different antenna heights, two different testing heights of the tags were necessary; these heights were 2.5 feet and 5 feet. Figure 18 shows a diagram of the experiment setup.

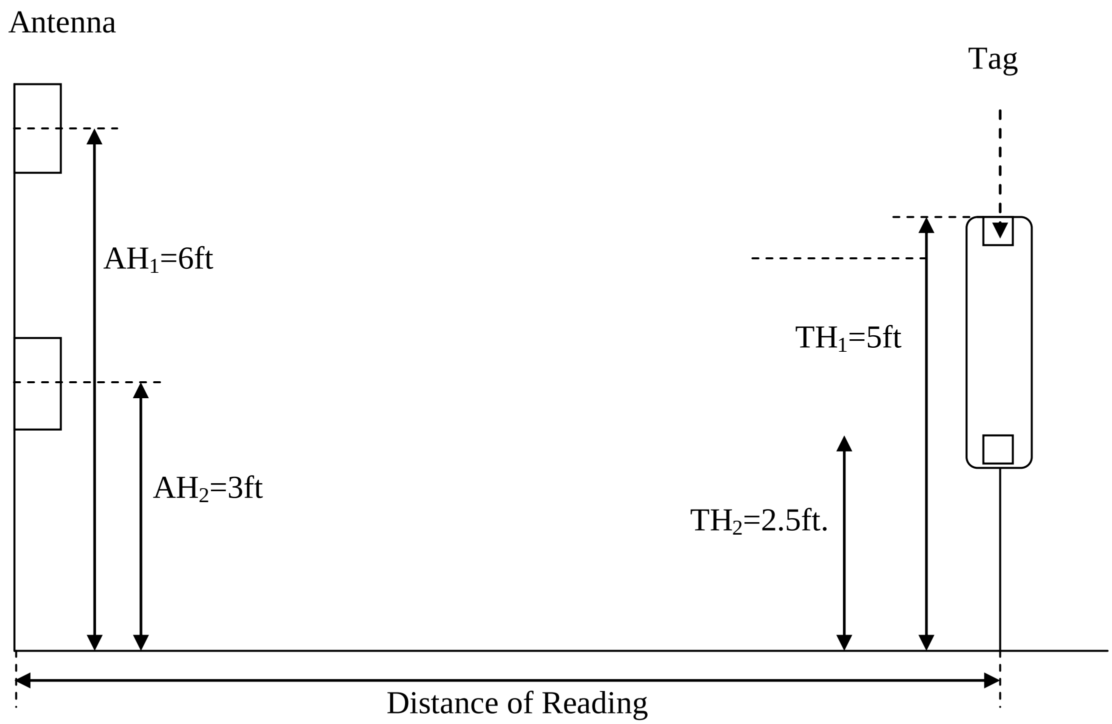

Figure 18. Design of the Experiment

This experiment was setup using a full factorial 2^2 design. The dependent variable for this study was distance, and the independent variables were antenna height (3ft, 6ft), and tag height (2.5ft, 5ft). Because the two independent variables are comprised of two factors each the DOE is called a full factorial 2^2 design (Montgomery).

The measurements were taken at different distances from the antennas depending on the strength between antenna and tag. When the tag was read by the antenna, the assigned name for that tag was displayed on the computer screen and the corresponding signal strength was recorded. The antenna was mounted on a vertical stand that could be moved to the various distance markers. The measurements were taken by starting at the furthest distance away from the tags and then moving forward in one foot increments until the first reading was achieved. This process was repeated for each variable of the experiment.

7.4.1 Distance Study Results

In experiment number one the longest reading distance was 18 feet and the shortest reading distance was 4 feet, therefore bringing the range to 14 feet. The mode and mean for the experiment were 9 feet and 9.35 feet (See Table 19 and Figure 19).

Table 19. RFID Tags Distance at First Reading Experiment 1

Observation Number	Tag Number	Starting Distance (ft)	Distance of Reading (ft)
1	No. 1	16	10
2	No. 2	16	9
3	No. 3	16	9
4	No. 3	16	10
5	No. 4	16	8
6	No. 5	16	8
7	No. 6	11	9
8	No. 7	14	7
9	No. 8	12	9
10	No. 9	12	9
11	No. 10	18	18
12	No. 11	19	9
13	No. 12	14	4
14	No. 13	16	8
15	No. 14	12	9
16	No. 15	14	8
17	No. 16	13	11
18	No. 17	13	11
19	No. 18	19	11
20	No. 19	13	10

Range	14 ft.
Mode	9 ft.
Mean	9.35 ft.

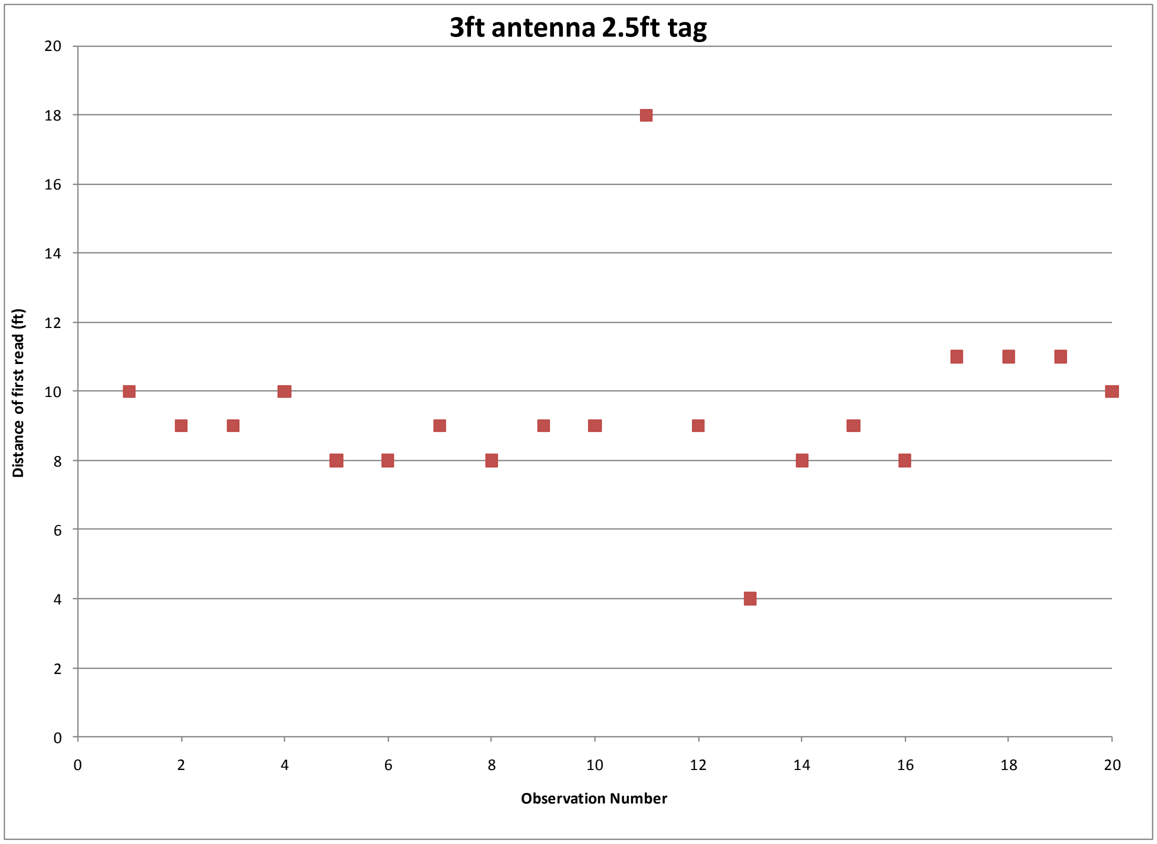

Figure 19. Performance of Results for Experiment 1

In experiment number two the longest reading distance was 17 feet and the shortest reading distance was 5 feet, therefore bringing the range to 12 feet. The mode and mean for the experiment were 10 feet (See Table 20 and Figure 20).

Table 20. RFID Tags Distance at First Reading Experiment 2

Observation Number	Tag Number	Starting Distance (ft)	Distance of Reading (ft)
21	No. 18	18	10
22	No. 17	17	16
23	No. 16	17	10
24	No. 15	17	8
25	No. 14	19	11
26	No. 13	19	8
27	No. 12	19	10
28	No. 11	17	17
29	No. 10	18	6
30	No. 19	18	10
31	No. 1	17	10
32	No. 2	17	9.5
33	No. 6	17	9
34	No. 3	15	11
35	No. 4	15	10
36	No. 5	15	9
37	No. 7	18	5
38	No. 8	14	11
39	No. 9	17	9.5

Range	12 ft.
Mode	10 ft.
Mean	10 ft.

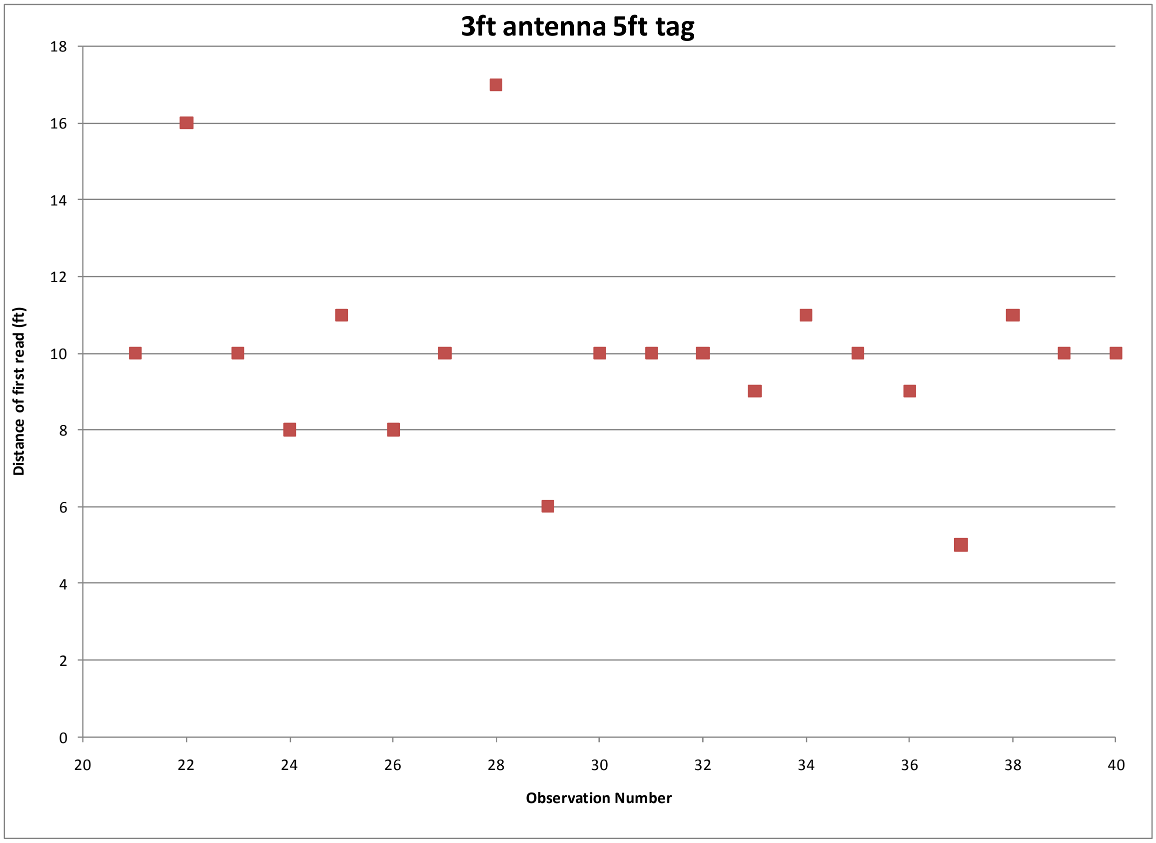

Figure 20. Performance of Results Experiment 2

In experiment number three the longest reading distance was 10 feet and the shortest reading distance was 4 feet, resulting in a range of 6 feet. The mode and mean for the experiment were 7 feet and 6.74 feet. (See Table 21 and Figure 21).

Table 21. RFID Tags Distance at First Reading Experiment 3

Observation Number	Tag Number	Starting Distance (ft)	Distance of Reading (ft)
40	No. 9	18	4
41	No. 8	12	10
42	No. 7	14	7
43	No. 5	13	6
44	No. 4	11	5
45	No. 3	10	8
46	No. 6	10	10
47	No. 2	11	5
48	No. 1	11	10
49	No. 19	11	7
50	No. 18	10	7
51	No. 10	10	7
52	No. 11	10	10
53	No. 12	10	7
54	No. 13	10	6
55	No. 15	11	5
56	No. 17	10	7
57	No. 14	10	7
58	No. 16	10	5

Range	6 ft.
Mode	7 ft.
Mean	6.74 ft.

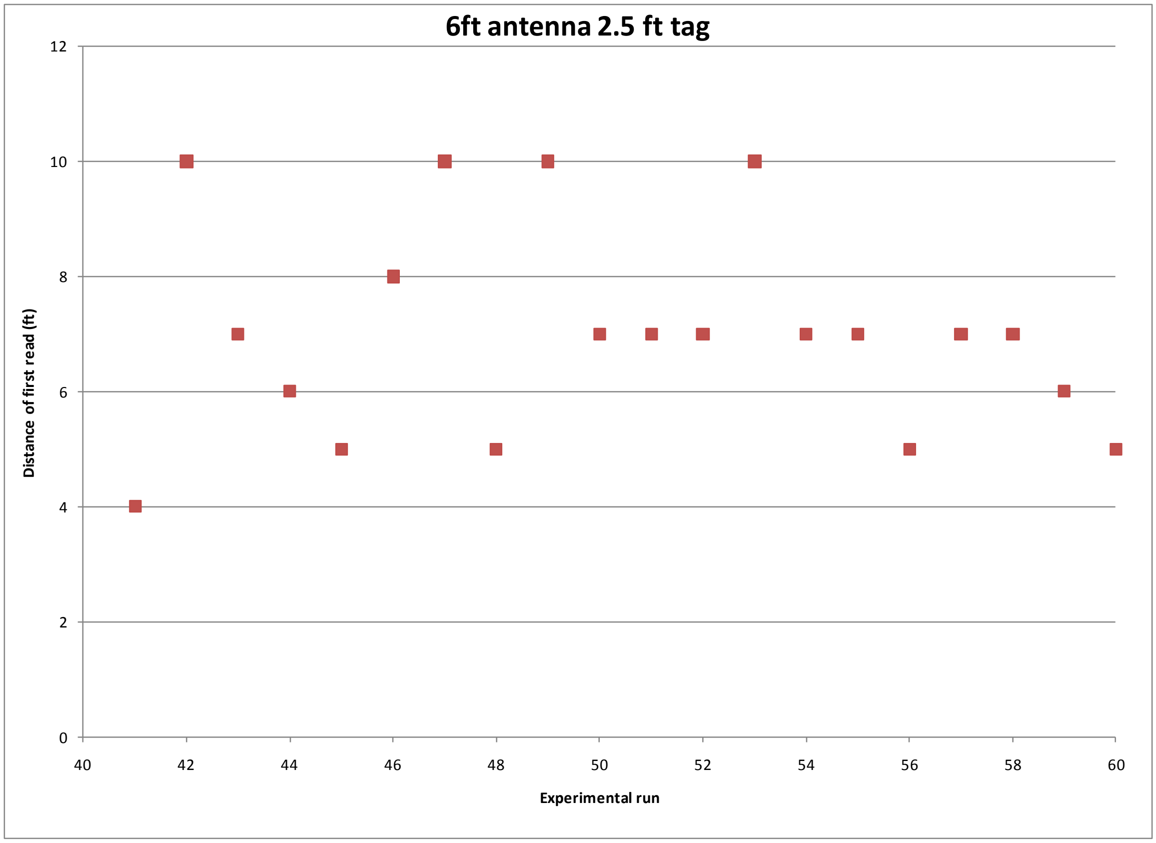

Figure 21. Performance of Results Experiment 3

In experiment number four the longest reading distance was 14 feet and the shortest reading distance was 5 feet, therefore the range was 9 feet. The mode and mean for the experiment were 9 feet and 9.6 feet (See Table 22 and Figure 22).

Table 22. RFID Tags Distance at First Reading Experiment 4

Observation Number	Tag Number	Starting Distance (ft)	Distance of Reading Result (ft)
59	No. 13	19	9
60	No. 15	14	5
61	No. 12	11	9
62	No. 11	10	9
63	No. 17	12	5
64	No. 10	12	9
65	No. 18	11	9
66	No. 19	11	9
67	No. 1	14	12
68	No. 2	14	14
69	No. 6	14	9
70	No. 3	13	13
71	No. 4	15	9
72	No. 5	13	8
73	No. 7	13	9
74	No. 8	13	9
75	No. 9	13	13
76	No. 14	13	13
77	No. 16	13	9

Range	9 ft.
Mode	9 ft.
Mean	9.6 ft.

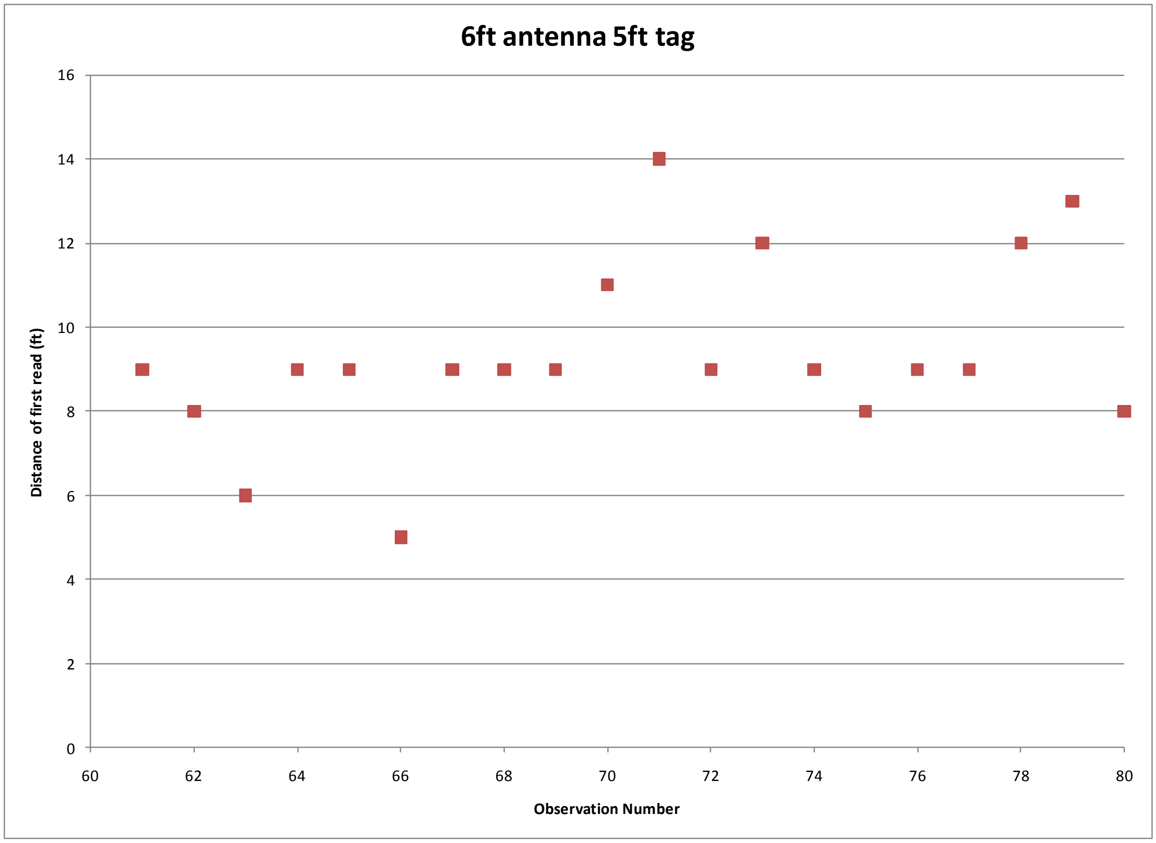

Figure 22. Performance of Results Experiment 4

The furthest readings were obtained when the antenna was at 6 feet and the tag was at 5 feet. The shortest reading occurred when the antenna was at 6 feet and the tag was at 2.5 feet, histograms for all experiments can be found Appendix H.

7.4.2 Anovna results

The results from the experiments indicate in Table 23 that the two specified factors antenna height and tag height are significant, but once again the interaction between these two variables is also significant. Because the interaction between the independent variables is significant it is hard to draw any conclusions about the antenna height or tag height. Once again, simple comparisons means across the two levels of the two independent variable antennal height and tag height indicate that all of height levels are statically significant at a confidence level of 95% (see antenna height and tag height pairwise comparisons table in Appendix J). Unfortunately the R2 value is very low indicating that the model is not a good fit for the data.

Table 23. ANOVA for passive distance read tests

Dependent Variable: Distance (ft)

Source	Type III Sum of Squares	df	Mean Square	F	P value.
AntennaHeight	158.203	1	158.203	28.769	.000
Tagheight	189.112	1	189.112	34.390	.000
AntennaHeight * Tagheight	58.653	1	58.653	10.666	.001
Error	1737.719	316	5.499		
Total	27526.500	320			
Corrected Total	2143.687	319			

a. R Squared = .189 (Adjusted R Squared = .182)

7.5 Performance of Active Tag System License plate

Since the passive tags were tested for performance an experiment was also setup to yield information the how the more expensive active system would perform in the field. The performance results were based upon Received Signal Strength Indication (RSSI). There were 20 trials taken for each variable for each condition tested. Only 20 trials were taken with 15 measurements in each trial due to time constrains and the limited difference variability in the results from measurement to measurement.

The equipment used for this experiment was the SAVi® SR-650 fixed reader, SAVi® Tag ST-654, SAVi SmartChain® Site Manager Software system. Figure 23 shows the apparatus.

Figure 23. Apparatus for Active Tag study

The outdoor testing procedure followed was to stand at specified horizontal distance from the fixed reader to the tag: 1, 3, 5, 10, 15, 20, 25, 30, 35, 40, 45, and 50 feet. The Savi SR-650 fixed reader was 5 feet high from the ground, while Savi tag ST-654 with the license plate was 2 feet high from the ground. The tag was put in-between the two pieces of license plates to simulate the metal to metal contact that would occur with an e-plate. Because there was one variable with 12 levels and for each level there were 20 readings taken, this resulted in a total of 12*20=240 trails.

First, the data was collected and then the given data for each horizontal distance were calculated to an average number. Second the plot was determined by the average numbers for every distance on a graph by using Microsoft Excel. After this process, it is evident by analyzing the trend of the RSSI changing with horizontal distance, that RSSI is reduced with the tag further from the fixed reader as a whole direction. After 35 feet, RSSI is increased with the tag further until arriving at a small peak at 45 feet. It is evident that the RSSI is still smaller than at a distance of 20 feet (Figure 24). What this means is that for maximum signal strength the tag can be no further than 20 feet from the reader. Even though the signal strength did increase again there are several other factors that should be analyzed to determine if the RSSI readings after 35 feet are valid. These reads could be ghost reads or can be caused by interference.

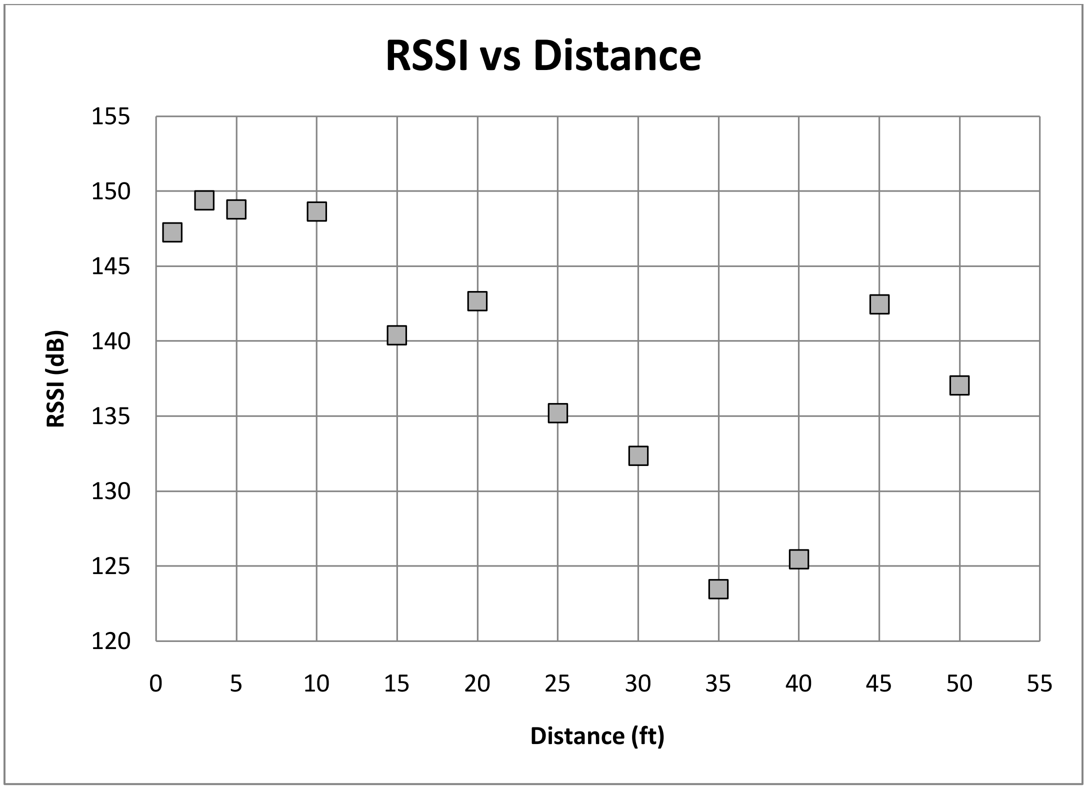

Figure 24. RSSI by Savi fixed reader

7.6 Additional results

Other RFID tag studies conducted by the RfCSL after the aforementioned initial testing yielded that the tags were readable on cars. The e-plate system was tested outside on a vehicle traveling 25 mph to explore the effect of horizontal distance versus RSSI received by E-plate software system between a fixed reader and tag on the in the field see Figure 25.

Figure 25. Apparatus e-plate field test

This testing was conducted by the RfSCL at the University of Nebraska. It was found that the RSSI changes dramatically, so the horizontal distance is a significant factor on impacting the RSSI. Additionally, RSSI reads were the strongest where the horizontal distance equals to 25 ft. Since the RSSI values are lower than the outdoor acceptable threshold of 75dB the tags will have a low reliability. The 75dB RSSI threshold level is considered the minimum signal strength for RFID to account for outside electromagnetic interference. The results of the test can be seen in Figure 26.

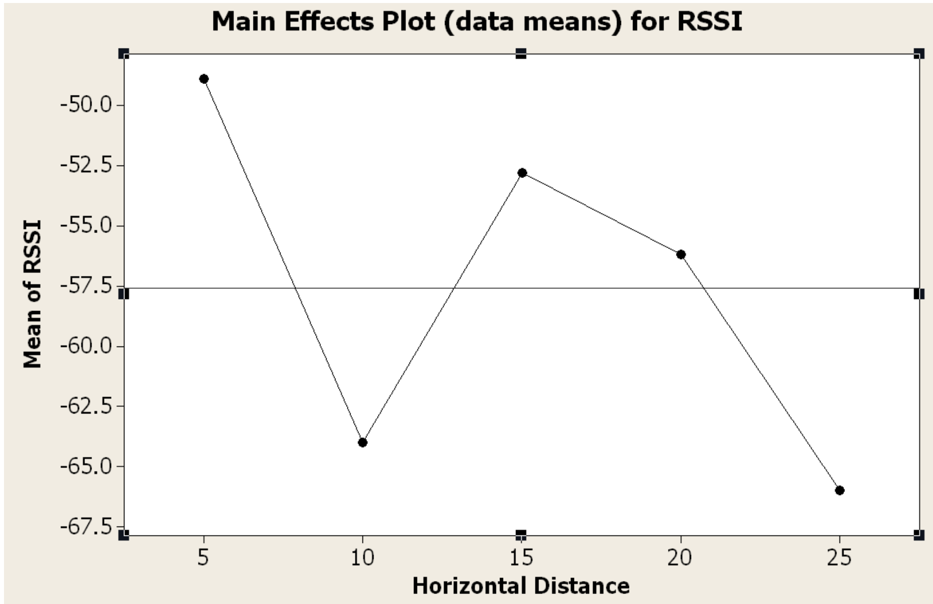

Figure 26. Result of Experiment

7.7 Summary

The location of the passive tag on license plates proved not to be a factor, while the other independent variables horizontal distance and vertical height were found to be significant factors impacting the signal strength. So two of the hypotheses for the location of the tag were false and the hypotheses for the tag height and distance proved to be true. The passive tags proved readable for the outdoors with a mean of 9 to 10 feet for the baseline test, and the tags were readable when mounted to a vehicle and driven at 25 mph, even though the RSSI was below the acceptable outdoor threshold. This reduced RSSI could be due to the high metal content of the vehicle interfering with the backscatter of the signal.

CHAPTER 8 CONCLUSION

From the stakeholder House of Quality data, the most significant areas are: the reliability of RFID tags inside license plates, the relevancy to current databases for the different departments, the price of RFID tags, increased mileage traveled using RFID, and so on. The HOQ analysis also determined the most important items that should be improved in technical requirements. Based on previous experiments, the requirement of displaying relevant information and RFID tag numbers are not significant difficulties. Using RFID in transportation system is valuable, and the research in this field is beneficial to improving current techniques.

The passive tags used in Experiment #1 are most often used for short read range applications. Because of the short read range, the experiment required a high powered reader. The strength of RFID related directly to frequency band. The frequency bands come in three categories which are low, medium, and high. High ranges from 850 to 950 MHz and 2.4 to 5.8 GHz, while medium ranges from 10 to15 MHz. On the other hand, the frequency band used for this research was “low” and ranged from 30 to 500 kHz. The characteristics for a Low Frequency include a short to medium read range, inexpensiveness, and a low reading speed. The applications that are usually tied to this particular frequency band are inventory and access control, car immobilizer, and animal identification. Experiment results demonstrate that Generation 2 tags can read at higher distances than 10 feet but height is a major factor. There are 5 vital areas that are tied directly to the performance and readability and read range of RFID: power to tag, power to reader, internal attenuation of signal, transmittance frequency, and environmental conditions.

Most importantly, environmental conditions were a major factor in this specific experiment. These conditions include moisture, obstructions from objects (including metal), and interfering sources with the same frequencies as the reader. Signal strength relates directly to how many times the tag can be read per second or nanosecond. If the antenna/reader is not elevated high enough, the signal will not be strong enough. Based on the experiment result, a suitable height range for the RFID measurement is revealed. The best range of suggested height of passive tags is around 3 feet, and it means that it is better to be closer to the antenna in the horizontal level. For active tags, the good range of suggested height is around 2 feet, which means there is the best angle between the tag and antenna (5 feet high) in this level. This is because the earth's surface is an electron sink and also has a magnetic field that may interfere with the connection between the antenna and the tag. So when using an electromagnetic device, a strong possibility exists that the RFID waves will experience interference. It is also stressed that when using equipment from a specific manufacturer, it is vital that the manual is followed in order to get a good signal reading.

In the passive testing experiment, an analysis of the results showed that one of the most significant factors was distance. The read numbers greatly decreased with increasing distance up to our maximum tested distance of 10 feet. In active testing the results were not as uniform. However, reads were easily obtained to distances of up to 50 feet. Given the critical distances needed for reading tags would usually lie between 10 and 50 feet, active technology had the definite edge in reliability. Further studies need to be done to determine if other factors, such as reader power, may allow passive technologies for the purpose of embedded license plates.

AHP methods in general, are highly effective for identifying conflicts between stakeholder groups, but not particularly useful for dispute resolution. The AHP analysis yields that having a reliable system is more important to the Nebraska transportation stakeholders than the ability to network the readers or use current infrastructure. The NDOR analysis was inconsistent and may be due to combining both the ITS and Planning divisions into one preference ranking. The inconsistency might also stem from possible rank reversal. This can occur when a stakeholder inadvertently switches preference during the rankings. The AHP excel file that was developed for this study can be used for further stakeholder analysis and when the State transportation officials are trying to decide on which new ITS system to implement this tool can be used to highlight preferences based on alternatives as well as providing a benefit cost analysis.

8.1 Future Research

Based on the results of this research, the following items are suggested for future projects:

- Conduct interviews with the same representatives from each individual stakeholder group to gain a more specific understanding of project requirements and the implications of those requirements.
- Conduct more thorough physical testing in outdoor environments and with embedded RFID transponders. Active technologies should also be further explored for this application.
- Setup a RFID portal test bed to demonstrate the capability of the License Plate System on an actual roadway using CVOs or representative vehicles.
- Expand how RFID can be used for traffic counts and pattern development. The use of RFID could allow for more accurate real-time monitoring of traffic trends used for planning and maintenance.
- Research fusion technologies that can use multiple transponder frequencies to solve incompatibility problems. This would allow for one transponder that can use RFID frequencies as well as PrePass and NorPass technologies.

8.2 Limitations

Due to the outdoor nature of the reliability study it was hard to limit the environmental factors, and any electromagnetic interference that might have occurred. Initial testing and baseline studies should be conducted in an anechoic chamber to test signal strength and read distances prior to the outdoor study. Additional limiting factors contributing to the research were introduced during the stakeholder analysis. For several of the meetings there were different representatives from each of the transportation groups, and each individual might have different opinions and preferences.

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APPENDIX A CRITICAL F VALUES

Table of Critical F Values
[top entry for .05 level; bottom entry for .01 level]

df denominator	df numerator 1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	161	199	216	225	230	234	237	239	241	242	243	244	245	245
	4052	4999	5404	5624	5764	5859	5928	5981	6022	6056	6083	6107	6126	6143
2	18.51	19.00	19.16	19.25	19.30	19.33	19.35	19.37	19.38	19.40	19.40	19.41	19.42	19.42
	99	99	99	99	99	99	99	99	99	99	99	99	99	99
3	10.13	9.55	9.28	9.12	9.01	8.94	8.89	8.85	8.81	8.79	8.76	8.74	8.73	8.71
	34.12	30.82	29.46	28.71	28.24	27.91	27.67	27.49	27.34	27.23	27.13	27.05	26.98	26.92
4	7.71	6.94	6.59	6.39	6.26	6.16	6.09	6.04	6.00	5.96	5.94	5.91	5.89	5.87
	21.20	18.00	16.69	15.98	15.52	15.21	14.98	14.80	14.66	14.55	14.45	14.37	14.31	14.25
5	6.61	5.79	5.41	5.19	5.05	4.95	4.88	4.82	4.77	4.74	4.70	4.68	4.66	4.64
	16.26	13.27	12.06	11.39	10.97	10.67	10.46	10.29	10.16	10.05	9.96	9.89	9.82	9.77
6	5.99	5.14	4.76	4.53	4.39	4.28	4.21	4.15	4.10	4.06	4.03	4.00	3.98	3.96
	13.75	10.92	9.78	9.15	8.75	8.47	8.26	8.10	7.98	7.87	7.79	7.72	7.66	7.60
7	5.59	4.74	4.35	4.12	3.97	3.87	3.79	3.73	3.68	3.64	3.60	3.57	3.55	3.53
	12.25	9.55	8.45	7.85	7.46	7.19	6.99	6.84	6.72	6.62	6.54	6.47	6.41	6.36
8	5.32	4.46	4.07	3.84	3.69	3.58	3.50	3.44	3.39	3.35	3.31	3.28	3.26	3.24
	11.26	8.65	7.59	7.01	6.63	6.37	6.18	6.03	5.91	5.81	5.73	5.67	5.61	5.56
9	5.12	4.26	3.86	3.63	3.48	3.37	3.29	3.23	3.18	3.14	3.10	3.07	3.05	3.03
	10.56	8.02	6.99	6.42	6.06	5.80	5.61	5.47	5.35	5.26	5.18	5.11	5.05	5.01
10	4.96	4.10	3.71	3.48	3.33	3.22	3.14	3.07	3.02	2.98	2.94	2.91	2.89	2.86
	10.04	7.56	6.55	5.99	5.64	5.39	5.20	5.06	4.94	4.85	4.77	4.71	4.65	4.60
11	4.84	3.98	3.59	3.36	3.20	3.09	3.01	2.95	2.90	2.85	2.82	2.79	2.76	2.74
	9.65	7.21	6.22	5.67	5.32	5.07	4.89	4.74	4.63	4.54	4.46	4.40	4.34	4.29
12	4.75	3.89	3.49	3.26	3.11	3.00	2.91	2.85	2.80	2.75	2.72	2.69	2.66	2.64
	9.33	6.93	5.95	5.41	5.06	4.82	4.64	4.50	4.39	4.30	4.22	4.16	4.10	4.05
13	4.67	3.81	3.41	3.18	3.03	2.92	2.83	2.77	2.71	2.67	2.63	2.60	2.58	2.55
	9.07	6.70	5.74	5.21	4.86	4.62	4.44	4.30	4.19	4.10	4.02	3.96	3.91	3.86
14	4.60	3.74	3.34	3.11	2.96	2.85	2.76	2.70	2.65	2.60	2.57	2.53	2.51	2.48
	8.86	6.51	5.56	5.04	4.69	4.46	4.28	4.14	4.03	3.94	3.86	3.80	3.75	3.70
15	4.54	3.68	3.29	3.06	2.90	2.79	2.71	2.64	2.59	2.54	2.51	2.48	2.45	2.42
	8.68	6.36	5.42	4.89	4.56	4.32	4.14	4.00	3.89	3.80	3.73	3.67	3.61	3.56

APPENDIX B HOQ ANALYSIS

Customers Requirements / Technical Requirements	RFID tag (Transponder) Read Distnace	Physical Limitation	Read Rate	Display Relevant Information	RFID tag number	Manufacturing Cost	Importance	Mission Critical	Project Critical	Absolute weight
Data Capture	●	●	o	●	●	Δ	10	5	2	100
Design for Non-weigh station Prepass Usage	Δ	●	o	o	o	o	5	3	2	30
Better performance than other Transponder Systems	●	o	o	●	o		5	3	1	15
Simplify Audit Process	●	●	●	●	●		5	1	1	5
Increased Audit Area using Roadside Readers				●	●	●	1	3	2	6
Improve Safety Process				●	●	o	5	3	1	15
Ability to Use of Current Databases	Δ	Δ	Δ	●	●	Δ	10	5	2	100
Target value	4	5	3	2	1	6				
Absolute weight	195	205	115	339	309	59				
Absolute factor	0.16	0.17	0.09	0.28	0.25	0.05				
Relative weight	1210	1360	580	2259	2169	389				
Relative factor	0.15	0.17	0.07	0.28	0.27	0.05				

HOQ for CED

Customers Requirements / Technical Requirements	RFID tag (Transponder) Read Distance	Physical Limitation	Read Rate	Display Relevant Information	RFID tag number	Manufacturing Cost	Importance	Mission Critical	Project Critical	Absolute weight
Ensure embedded RFID chip inside License plate works	●	●	○	●	○	Δ	10	5	2	100
Work with Suppliers	Δ	Δ	Δ	Δ	Δ	●	5	5	2	50
Design working RFID License plate manufacturing process	○	○	○	○	Δ	●	10	5	2	100
Production Cost	○	○	Δ	○	○	●	5	3	1	15
Target value	4	1	5	1	6	1				
Absolute weight	140	140	70	140	60	55				
Absolute factor	0.23	0.23	0.12	0.23	0.10	0.09				
Relative weight	1295	1295	665	1295	495	1585				
Relative factor	0.20	0.20	0.10	0.20	0.07	0.24				

HOQ for CSI

Customers Requirements / Technical Requirements	RFID tag (Transponder) Read Distance	Physical Limitation	Read Rate	Display Relevant Information	RFID tag number	Manufacturing Cost	Importance	Mission Critical	Project Critical	Absolute weight
Motor Carrier Division				●	●	○	10	5	2	100
CVIEW				●	●	○	10	5	2	100
Increased Mileage Traveled using Readers	○	●	○	●	●	○	10	5	2	100
Integrating the Important Current System in RFID System				●	●		10	5	2	100
Improve Safety Process				●	●	○	5	3	1	15

	RFID tag (Transponder) Read Distance	Physical Limitation	Read Rate	Display Relevant Information	RFID tag number	Manufacturing Cost
Target value	5	3	5	1	1	3
Absolute weight	30	90	30	405	405	75
Absolute factor	0.03	0.09	0.03	0.39	0.39	0.07
Relative weight	300	900	300	3735	3735	945
Relative factor	0.03	0.09	0.03	0.38	0.38	0.10

HOQ for DMV

Customers Requirements \ Technical Requirements	RFID tag (Transponder) Read Distance	Physical Limitation	Read Rate	Display Relevent Information	RFID tag number	Manufacturing Cost	Importance	Mission Critical	Project Critical	Absolute weight
Integrating the Important Current System in RFID System				●	●		10	5	2	100
Placing more sensors in specific areas	●	●	o	●	o	Δ	5	3	1	15
Network all readers together			o	o	●	Δ	10	5	2	100
Ability to Use of Current Databases	Δ	Δ	Δ	●	●	Δ	10	5	2	100
Production Cost	o	o	Δ	o	o	●	5	3	1	15

	RFID tag (Transponder) Read Distance	Physical Limitation	Read Rate	Display Relevent Information	RFID tag number	Manufacturing Cost
Target value	5	5	3	2	1	3
Absolute weight	70	70	60	270	300	50
Absolute factor	0.09	0.09	0.07	0.33	0.37	0.06
Relative weight	280	280	460	2280	2790	350
Relative factor	0.04	0.04	0.07	0.35	0.43	0.05

HOQ for NDOR-ITS

Customers Requirements \ Technical Requirements	RFID tag (Transponder) Read Distance	Physical Limitation	Read Rate	Display Relevant Information	RFID tag number	Manufacturing Cost	Importance	Mission Critical	Project Critical	Absolute weight
Traffic Counting	●	●	○	●	●	Δ	10	5	2	100
Use RFID in the Place of present radar	○	○	○	●	●	Δ	5	1	1	5
Enhance road operations (maintenance)				Δ		Δ	1	1	1	1
Range of reader	●	●	●	Δ	Δ		3	3	1	9
Target value	1	1	5	3	3	6				
Absolute weight	132	132	72	139	138	15				
Absolute factor	0.21	0.21	0.11	0.22	0.22	0.02				
Relative weight	996	996	396	955	954	106				
Relative factor	0.23	0.23	0.09	0.22	0.22	0.02				

HOQ for NDOR-Planning

Customers Requirements / Technical Requirements	RFID tag (Transponder) Read Distance	Physical Limitation	Read Rate	Display Relevant Information	RFID tag number	Manufacturing Cost	Importance	Mission Critical	Project Critical	Absolute weight
Tracking of Individuals, especially non-compliant CVO license plates	●	○	●	○	○	Δ	10	5	2	100
Range of reader	●	●	●	Δ	Δ		3	3	1	9
Speed Enforcement	○	○	●	Δ	●	Δ	5	3	2	30
Mobile Vehicle Data Collection	●	●	Δ	○	●	Δ	10	3	1	30
Access Control	Δ	Δ	Δ		●	Δ	5	3	1	15
Ability to Use of Current Databases	Δ	Δ	Δ	●	●	Δ	10	5	2	100
Target value	2	5	4	3	1	6				
Absolute weight	237	177	187	158	303	25				
Absolute factor	0.22	0.16	0.17	0.15	0.28	0.02				
Relative weight	1456	856	1396	1329	1884	275				
Relative factor	0.20	0.12	0.19	0.18	0.26	0.04				

HOQ for NSP

APPENDIX C AHP ANALYSIS

NDOR Data

	Data Capture	Traffic Counting	Networked Readers	Working Plate	Tracking CVO	Interoperable
Data Capture	1	1/2	1	5	6	3
Traffic Counting	2	1	3	1/4	5	8
Networked Readers	1	1/3	1	6	7	6
Working Plate	1/5	4	1/6	1	6	4
Tracking CVO	1/6	1/5	1/7	1/6	1	1/5
Interoperable	1/3	1/8	1/6	1/4	5	1
Sum	4.7	6.158333	5.47619048	12.66667	30	22.2

Normalize relative weight

	0.212766	0.081191	0.182609	0.394737	0.2	0.135135
	0.425532	0.162382	0.547826	0.019737	0.166666667	0.36036
	0.212766	0.054127	0.182609	0.473684	0.233333333	0.27027
	0.042553	0.649526	0.030435	0.078947	0.2	0.18018
	0.035461	0.032476	0.026087	0.013158	0.033333333	0.009009
	0.070922	0.020298	0.030435	0.019737	0.166666667	0.045045
Sum	1	1	1	1	1	1

	0.201073
	0.280417
W=	0.237798
	0.19694
	0.024921
	0.058851
Sum	1

λ= 8.522855256
RI= 1.24

CI= 0.504571
CR= 0.406912

20.11%	1.39
28.04%	1.00
23.78%	1.18
19.69%	1.42
2.49%	11.25
5.89%	4.76

CED Data

	Data Capture	Traffic Counting	Networked Readers	Working Plate	Tracking CVO	Interoperable
Data Capture	1	6	3	4	5	2
Traffic Counting	1/6	1	1/3	1/2	1	1/4
Networked Readers	1/3	3	1	3	2	1/2
Working Plate	1/5	2	1/3	1	2	1/3
Tracking CVO	1/4	1	1/2	1/2	1	1/2
Interoperable	1/2	4	2	3	2	1
Sum	2	17	7	12	13	5

Normalize relative weight

	0.408163	0.352941	0.418605	0.333333	0.384615	0.436364
	0.068027	0.058824	0.0465116	0.041667	0.076923	0.054545
	0.136054	0.176471	0.139535	0.250000	0.153846	0.109091
	0.081633	0.117647	0.046512	0.083333	0.153846	0.072727
	0.102041	0.058824	0.069767	0.041667	0.076923	0.109091
	0.204082	0.235294	0.279070	0.250000	0.153846	0.218182
Sum	1	1	1	1	1	1

	0.389004
	0.05775
W=	0.160833
	0.092616
	0.076385
	0.223412
Sum	1

λ=	6.215816407	CI=	0.043163
RI=	1.24	CR=	0.034809

38.90%	1.00
5.77%	6.74
16.08%	2.42
9.26%	4.20
7.64%	5.09
22.34%	1.74

CSI Data

	Data Capture	Traffic Counting	Networked Readers	Working Plate	Tracking CVO	Interoperable
Data Capture	1	1	1	1	5	5
Traffic Counting	1	1	1/5	1/5	5	5
Networked Readers	1	5	1	1	5	5
Working Plate	1	5	1	1	5	5
Tracking CVO	1/5	1/5	1/5	1/5	1	3
Interoperable	1/5	1/5	1/5	1/5	1/3	1
Sum	4	12	4	4	21	24

Normalize relative weight

	0.227273	0.080645	0.277778	0.277778	0.234375	0.208333
	0.227273	0.080645	0.0555556	0.055556	0.234375	0.208333
	0.227273	0.403226	0.277778	0.277778	0.234375	0.208333
	0.227273	0.403226	0.277778	0.277778	0.234375	0.208333
	0.045455	0.016129	0.055556	0.055556	0.046875	0.125000
	0.045455	0.016129	0.055556	0.055556	0.015625	0.041667
Sum	1	1	1	1	1	1

	0.217697
	0.143623
W=	0.27146
	0.27146
	0.057428
	0.038331
Sum	1

λ=	6.838387459	CI=	0.167677
RI=	1.24	CR=	0.135224

21.77%	1.25
14.36%	1.89
27.15%	1.00
27.15%	1.00
5.74%	4.73
3.83%	7.08

NSP Data

	Data Capture	Traffic Counting	Networked Readers	Working Plate	Tracking CVO	Interoperable
Data Capture	1	8	1/2	1	1/6	2
Traffic Counting	1/8	1	1/7	1	1/8	1/7
Networked Readers	2	7	1	1	1/5	1
Working Plate	1	1	1	1	1/7	1/6
Tracking CVO	6	8	5	7	1	2
Interoperable	1/2	7	1	6	1/2	1
Sum	11	32	9	17	2	6

Normalize relative weight

	0.094118	0.250000	0.057851	0.058824	0.078081	0.316981
	0.011765	0.031250	0.0165289	0.058824	0.058561	0.022642
	0.188235	0.218750	0.115702	0.058824	0.093698	0.158491
	0.094118	0.031250	0.115702	0.058824	0.066927	0.026415
	0.564706	0.250000	0.578512	0.411765	0.468489	0.316981
	0.047059	0.218750	0.115702	0.352941	0.234244	0.158491
Sum	1	1	1	1	1	1

	0.142642
	0.033262
W=	0.13895
	0.065539
	0.431742
	0.187865
Sum	1

λ=	7.001940358	CI=	0.200388
RI=	1.24	CR=	0.161603

14.26%	3.03
3.33%	12.98
13.89%	3.11
6.55%	6.59
43.17%	1.00
18.79%	2.30

	Data Capture	Traffic Counting	Networked Readers	Working Plate	Tracking CVO	Interoperable
Data Capture	1	6	7	1	1	1
Traffic Counting	1/6	1	1	1/7	1/7	1
Networked Readers	1/7	1	1	1/7	1/7	1
Working Plate	1	7	7	1	2	7
Tracking CVO	1	7	7	1/2	1	1
Interoperable	1	1	1	1/7	1	1
Sum	4	23	24	3	5	12

Normalize relative weight

	0.232044	0.260870	0.291667	0.341463	0.189189	0.083333
	0.038674	0.043478	0.0416667	0.048780	0.027027	0.083333
	0.033149	0.043478	0.041667	0.048780	0.027027	0.083333
	0.232044	0.304348	0.291667	0.341463	0.378378	0.583333
	0.232044	0.304348	0.291667	0.170732	0.189189	0.083333
	0.232044	0.043478	0.041667	0.048780	0.189189	0.083333
Sum	1	1	1	1	1	1

	0.233094
	0.04716
W=	0.046239
	0.355206
	0.211885
	0.106415
Sum	1

λ=	6.636140395	CI=	0.127228
RI=	1.24	CR=	0.102603

23.31%	1.52
4.72%	7.53
4.62%	7.68
35.52%	1.00
21.19%	1.68
10.64%	3.34

	Data Capture	Traffic Counting	Networked Readers	Working Plate	Tracking CVO	Interoperable
Data Capture	1	5	4	5	4	3
Traffic Counting	1/5	1	1	1/3	3	3
Networked Readers	1/4	1	1	3	3	4
Working Plate	1/5	3	1/3	1	3	3
Tracking CVO	1/4	1/3	1/3	1/3	1	1
Interoperable	1/3	1/3	1/4	1/3	1	1
Sum	2	11	7	10	15	15

Normalize relative weight

	0.448279	0.464911	0.585608	0.497786	0.268189	0.200000
	0.089656	0.092982	0.1345504	0.033186	0.199068	0.200000
	0.112070	0.101172	0.146402	0.303412	0.199068	0.266667
	0.089656	0.278947	0.048038	0.099557	0.200964	0.200000
	0.110914	0.030994	0.048801	0.032873	0.066356	0.066667
	0.149426	0.030994	0.036601	0.033186	0.066356	0.066667
Sum	1	1	1	1	1	1

	0.410795
	0.124907
W=	0.188132
	0.15286
	0.059434
	0.063872
Sum	1

λ=	6.933921921	CI=	0.186784
RI=	1.24	CR=	0.150633

41.08%	1.00
12.49%	3.29
18.81%	2.18
15.29%	2.69
5.94%	6.91
6.39%	6.43

APPENDIX D LICENSE PLATE RAW DATA

Raw Test Data for license plate study

StdOrder	RunOrder	Blocks	Tag Height (ft)	Tag-Antenna Distance (ft)	Tag Location
81	1	3	3	10	Outside
67	2	3	2	5	Inside
70	3	3	2	10	Inside
64	4	3	2	1	Inside
62	5	3	1	10	In-between
61	6	3	1	10	Inside
80	7	3	3	10	In-between
76	8	3	3	5	Inside
78	9	3	3	5	Outside
75	10	3	3	1	Outside
55	11	3	1	1	Inside
79	12	3	3	10	Inside
72	13	3	2	10	Outside
65	14	3	2	1	In-between
57	15	3	1	1	Outside
59	16	3	1	5	In-between
66	17	3	2	1	Outside
74	18	3	3	1	In-between
71	19	3	2	10	In-between
73	20	3	3	1	Inside
63	21	3	1	10	Outside
68	22	3	2	5	In-between
77	23	3	3	5	In-between
58	24	3	1	5	Inside
60	25	3	1	5	Outside
69	26	3	2	5	Outside
56	27	3	1	1	In-between
83	28	4	1	1	In-between
87	29	4	1	5	Outside
82	30	4	1	1	Inside
91	31	4	2	1	Inside
84	32	4	1	1	Outside
108	33	4	3	10	Outside
88	34	4	1	10	Inside
97	35	4	2	10	Inside
99	36	4	2	10	Outside
105	37	4	3	5	Outside
94	38	4	2	5	Inside
101	39	4	3	1	In-between
104	40	4	3	5	In-between
102	41	4	3	1	Outside
95	42	4	2	5	In-between
98	43	4	2	10	In-between
96	44	4	2	5	Outside
92	45	4	2	1	In-between
90	46	4	1	10	Outside
86	47	4	1	5	In-between
93	48	4	2	1	Outside
89	49	4	1	10	In-between
103	50	4	3	5	Inside
106	51	4	3	10	Inside
107	52	4	3	10	In-between
85	53	4	1	5	Inside
100	54	4	3	1	Inside
135	55	5	3	10	Outside

Raw Test Data for license plate study page 2

130	56	5	3	5	Inside
126	57	5	2	10	Outside
112	58	5	1	5	Inside
119	59	5	2	1	In-between
117	60	5	1	10	Outside
122	61	5	2	5	In-between
118	62	5	2	1	Inside
120	63	5	2	1	Outside
116	64	5	1	10	In-between
129	65	5	3	1	Outside
124	66	5	2	10	Inside
114	67	5	1	5	Outside
132	68	5	3	5	Outside
128	69	5	3	1	In-between
127	70	5	3	1	Inside
123	71	5	2	5	Outside
125	72	5	2	10	In-between
110	73	5	1	1	In-between
133	74	5	3	10	Inside
131	75	5	3	5	In-between
115	76	5	1	10	Inside
109	77	5	1	1	Inside
111	78	5	1	1	Outside
113	79	5	1	5	In-between
121	80	5	2	5	Inside
134	81	5	3	10	In-between
35	82	2	1	10	In-between
49	83	2	3	5	Inside
39	84	2	2	1	Outside
41	85	2	2	5	In-between
29	86	2	1	1	In-between
47	87	2	3	1	In-between
45	88	2	2	10	Outside
50	89	2	3	5	In-between
40	90	2	2	5	Inside
52	91	2	3	10	Inside
37	92	2	2	1	Inside
30	93	2	1	1	Outside
31	94	2	1	5	Inside
38	95	2	2	1	In-between
51	96	2	3	5	Outside
43	97	2	2	10	Inside
42	98	2	2	5	Outside
32	99	2	1	5	In-between
33	100	2	1	5	Outside
28	101	2	1	1	Inside
54	102	2	3	10	Outside
34	103	2	1	10	Inside
36	104	2	1	10	Outside
53	105	2	3	10	In-between
46	106	2	3	1	Inside
48	107	2	3	1	Outside
44	108	2	2	10	In-between
11	109	1	2	1	In-between
14	110	1	2	5	In-between
25	111	1	3	10	Inside

Raw Test Data for license plate study page 3

5	112	1	1	5	In-between
1	113	1	1	1	Inside
21	114	1	3	1	Outside
18	115	1	2	10	Outside
17	116	1	2	10	In-between
3	117	1	1	1	Outside
19	118	1	3	1	Inside
27	119	1	3	10	Outside
9	120	1	1	10	Outside
13	121	1	2	5	Inside
26	122	1	3	10	In-between
16	123	1	2	10	Inside
22	124	1	3	5	Inside
4	125	1	1	5	Inside
8	126	1	1	10	In-between
24	127	1	3	5	Outside
10	128	1	2	1	Inside
15	129	1	2	5	Outside
6	130	1	1	5	Outside
20	131	1	3	1	In-between
12	132	1	2	1	Outside
7	133	1	1	10	Inside
23	134	1	3	5	In-between
2	135	1	1	1	In-between

APPENDIX E ACTIVE TAG RAW DATA

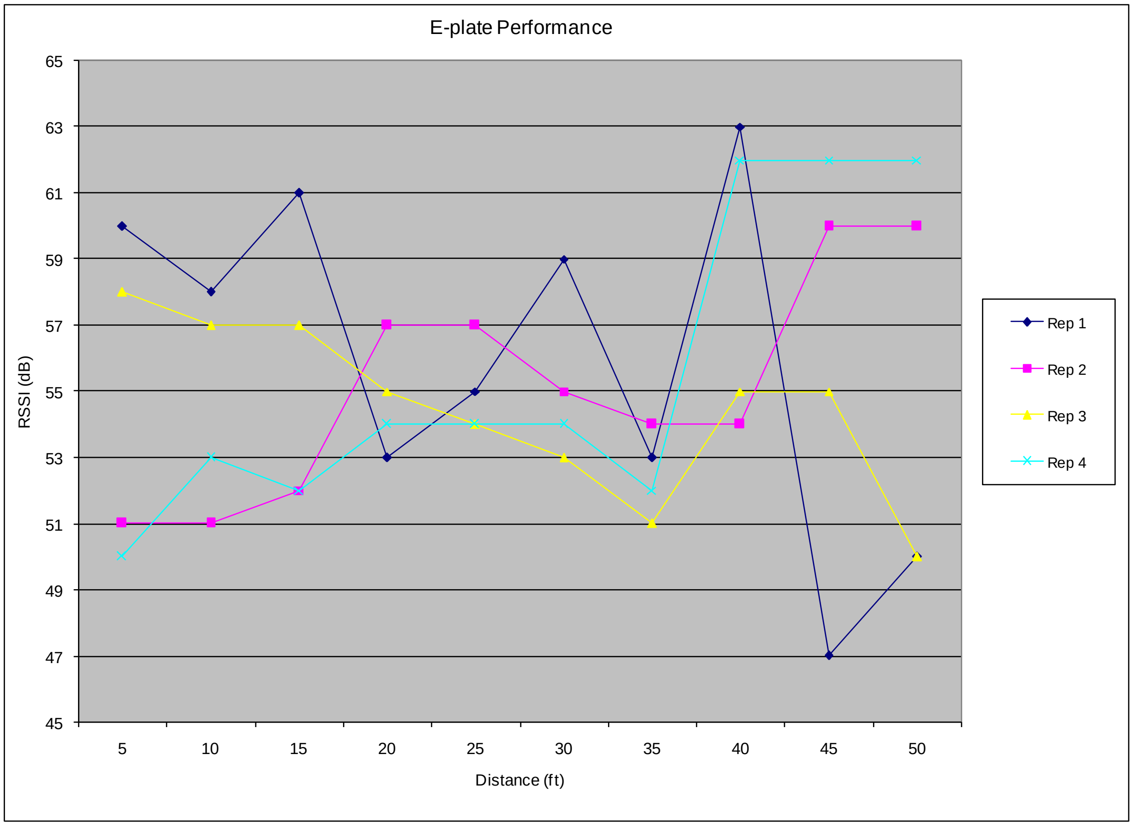
Active RSSI Study

Distance	1	3	5	10	15	20	25	30	35	40	45	50
Trial #												
1	141	139	139	140	141	134	138	132	102	134	140	137
2	149	144	149	138	141	120	131	131	130	109	149	137
3	151	151	149	151	151	151	140	146	110	124	140	138
4	150	151	151	151	150	151	137	137	139	129	149	137
5	141	151	150	151	143	142	143	125	112	130	149	132
6	150	151	152	151	149	105	87	125	104	96	140	135
7	150	151	151	151	143	148	101	126	104	130	149	137
8	149	151	151	142	142	147	140	124	104	95	148	135
9	149	151	151	151	150	143	143	110	113	130	141	139
10	148	151	141	151	147	147	130	105	115	93	140	137
11	149	151	151	151	150	142	136	123	115	129	140	139
12	149	151	150	150	150	143	144	123	104	130	135	138
13	148	151	151	151	136	150	141	141	130	140	135	140
14	149	151	150	150	130	150	141	146	143	139	137	137
15	148	142	150	150	129	149	141	147	142	140	137	139
16	149	150	139	151	129	150	140	141	144	140	149	137
17	128	151	150	151	130	149	140	141	127	140	148	138
18	149	150	150	141	130	142	140	141	147	101	137	136
19	149	150	150	150	136	141	147	142	148	140	149	137
20	149	150	151	151	131	149	144	141	136	140	137	136
Avg	147.25	149.4	148.8	148.65	140.4	142.65	135.2	132.35	123.45	125.45	142.45	137.05

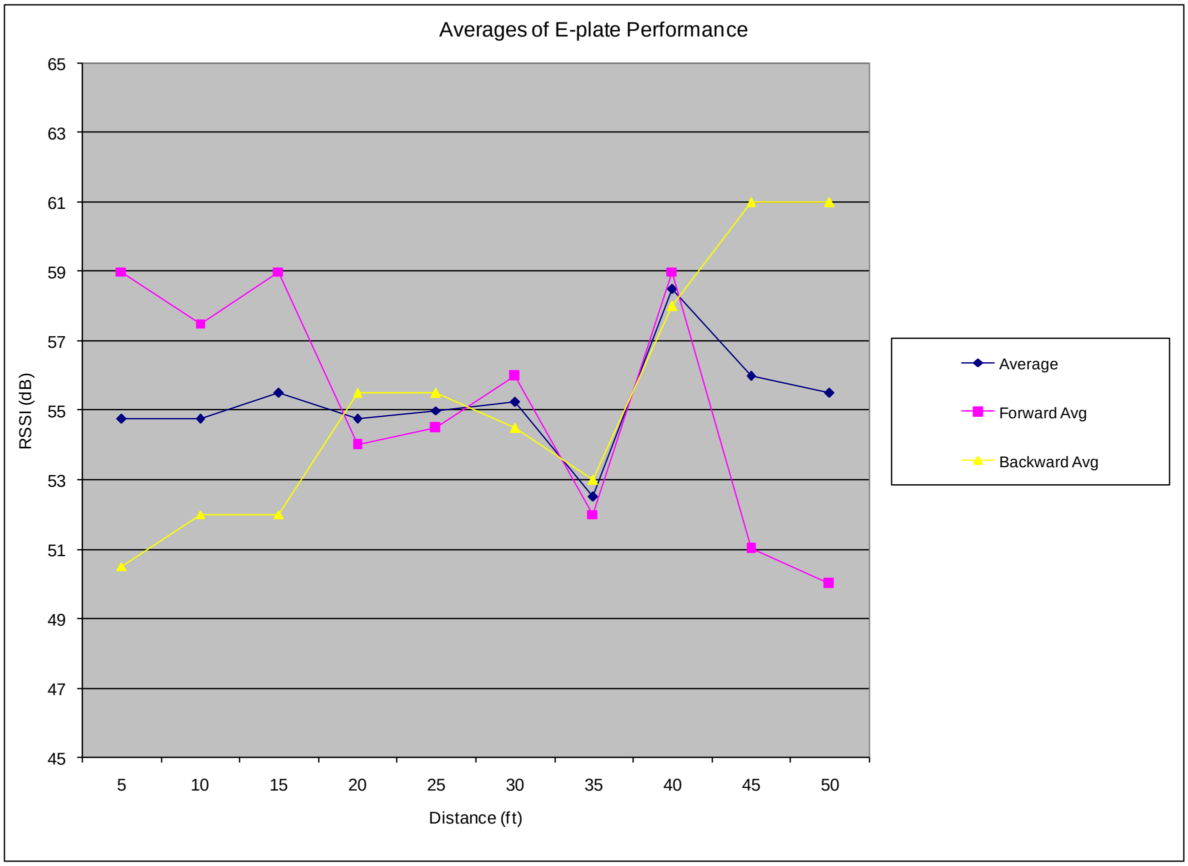
APPENDIX F SAMPLE E-PLATE DATA

Distance	Rep 1	Rep 2	Rep 3	Rep 4	Average	Forward Avg	Backward Avg
5	60	51	58	50	54.75	59	50.5
10	58	51	57	53	54.75	57.5	52
15	61	52	57	52	55.5	59	52
20	53	57	55	54	54.75	54	55.5
25	55	57	54	54	55	54.5	55.5
30	59	55	53	54	55.25	56	54.5
35	53	54	51	52	52.5	52	53
40	63	54	55	62	58.5	59	58
45	47	60	55	62	56	51	61
50	50	60	50	62	55.5	50	61

E-plate performance chart from data



E-plate Performance chart from data



APPENDIX G PASSIVE TAG RAW DATA

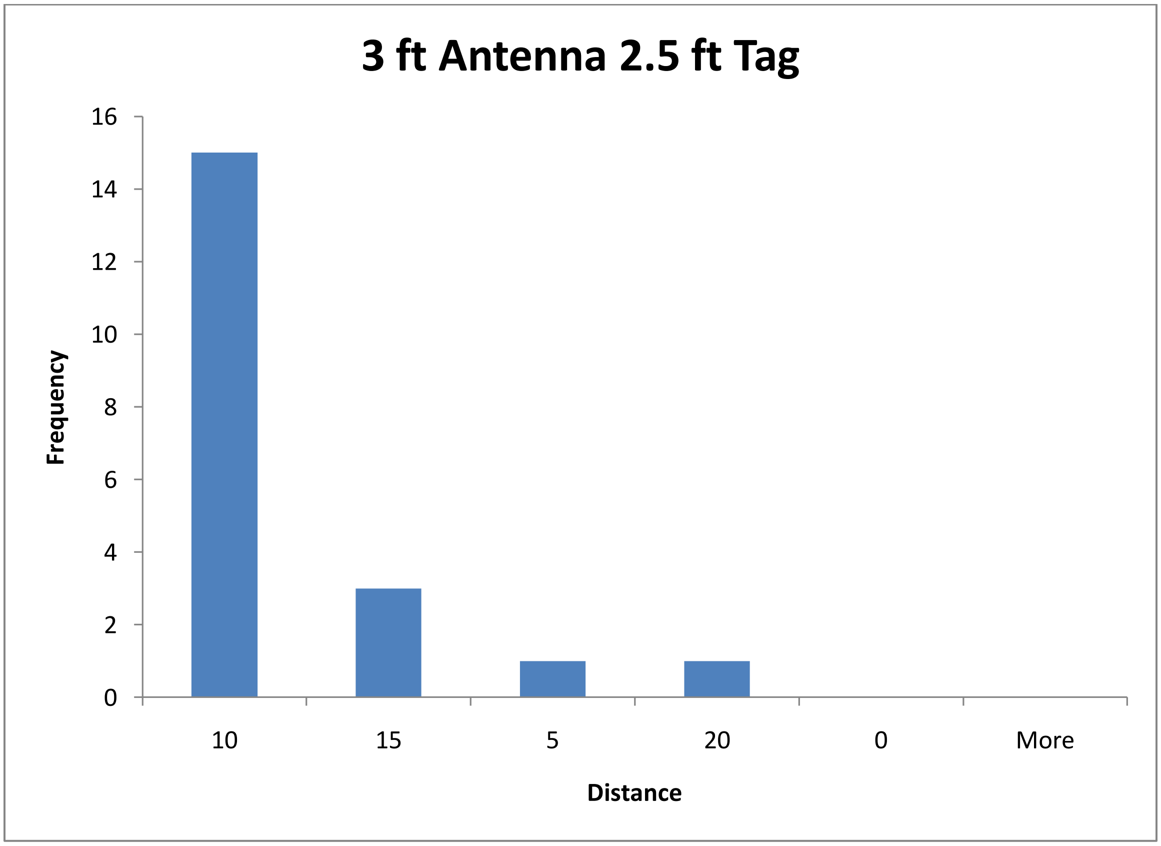
Antenna Height	Tag Height	Trail 1	Trail 2	Trail 3	Trail 4	Avg	
3	2.5	10	9	10	11	10	10
3	2.5	9	9	9	9	9	9
3	2.5	9	10	10	8	9.25	9
3	2.5	10	10	10	8	9.5	10
3	2.5	8	7	8	8	7.75	8
3	2.5	9	8	8	8	8.25	8
3	2.5	9	9	9	8	8.75	9
3	2.5	9	7	7	7	7.5	8
3	2.5	9	7.5	9	9	8.625	9
3	2.5	9	7	9	10	8.75	9
3	2.5	18	17	19	17	17.75	18
3	2.5	8	8	10	9	8.75	9
3	2.5	4	4	4	4	4	4
3	2.5	8	6	8	8	7.5	8
3	2.5	9	9	8	9	8.75	9
3	2.5	8	8.5	8	8	8.125	8
3	2.5	12	10	10	13	11.25	11
3	2.5	11	10	11	11	10.75	11

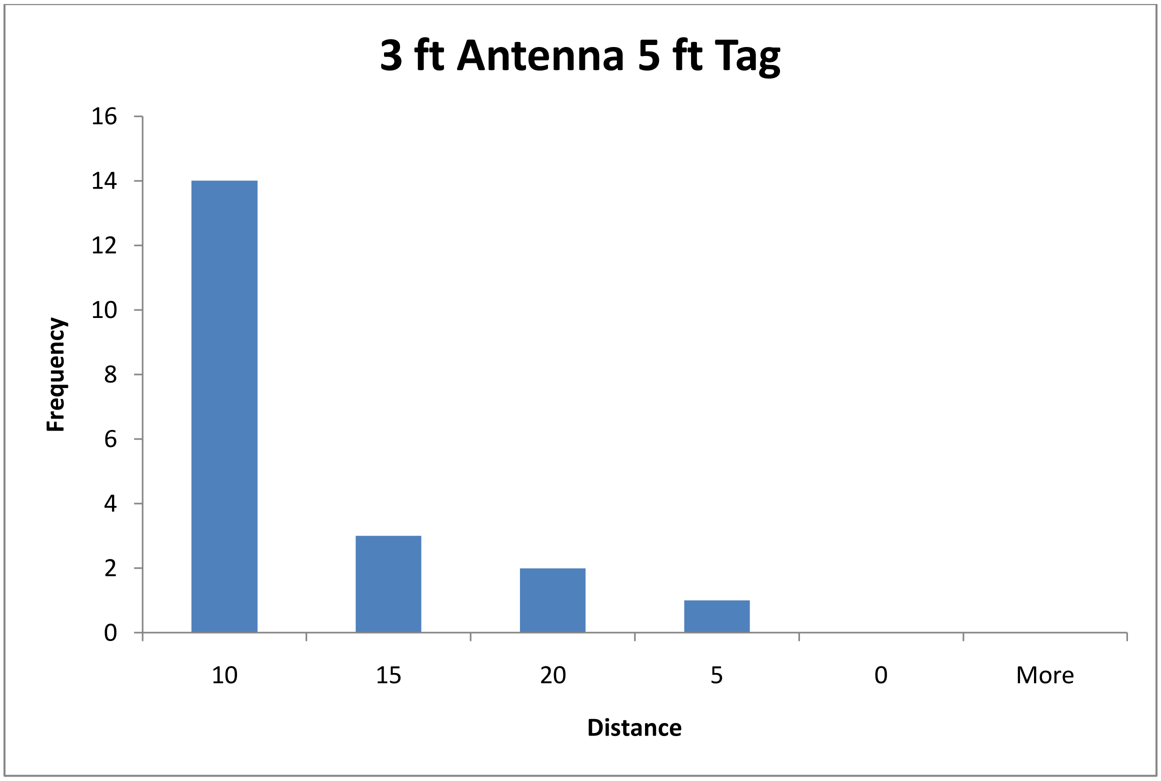
3	2.5	11	10	11	11	10.75	11
3	2.5	11	10	10.5	10	10.375	10
3	5	10	10	10	10	10	10
3	5	16	16	16	16	16	16
3	5	10	10	10	10	10	10
3	5	7.5	7.5	8	8	7.75	8
3	5	11	11	10.5	11	10.875	11
3	5	8	8	8	8	8	8
3	5	10	10	10	10	10	10
3	5	16	16.5	16.5	17	16.5	17
3	5	6	6	6	6	6	6
3	5	10	10	10	10	10	10
3	5	10	10	10	10	10	10
3	5	9.5	9	9.5	10	9.5	10
3	5	9	9	8	9	8.75	9
3	5	11	11	10	11	10.75	11
3	5	9.5	10	10	9.5	9.75	10
3	5	9	9	9	9	9	9
3	5	5	5	6	5.5	5.375	5
3	5	11	11	11	11	11	11
3	5	10.5	10	10	10	10.125	10

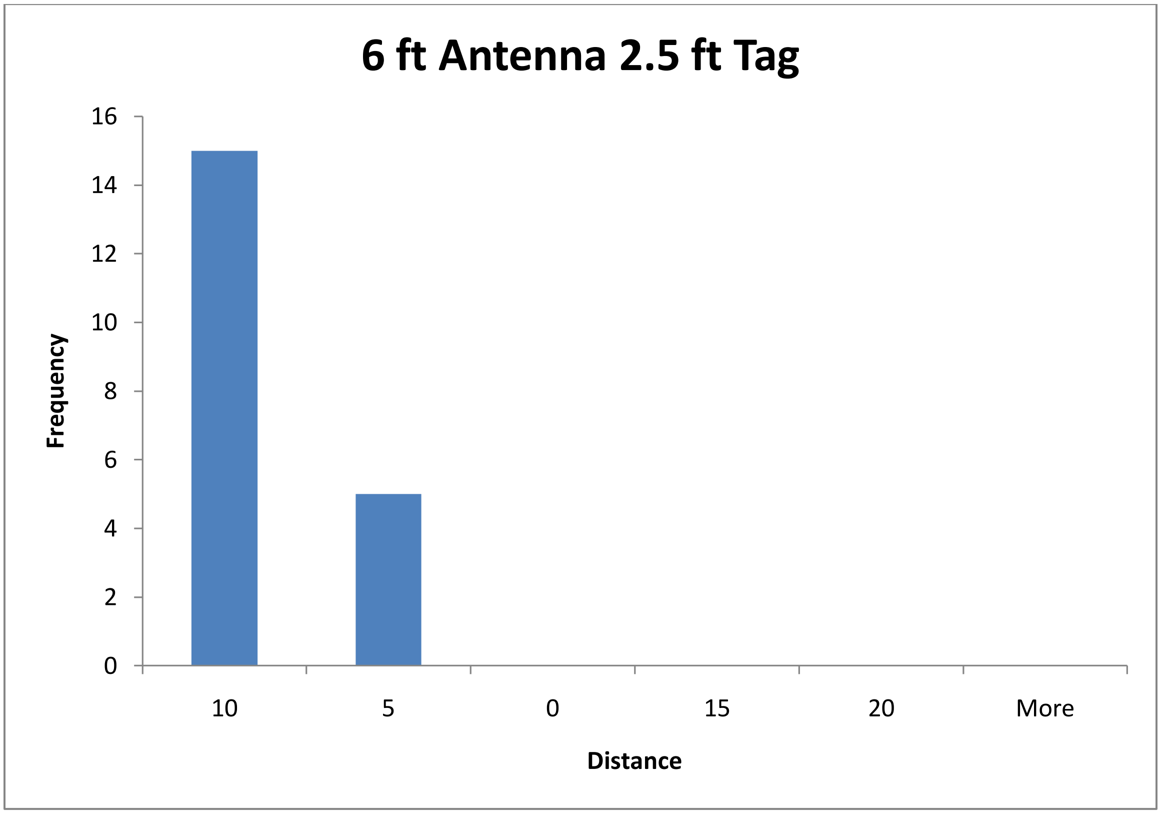
3	5	9.5	10	9	10	9.625	10
6	2.5	4	5	3.5	4	4.125	4
6	2.5	10	10	10	10	10	10
6	2.5	7	7.5	7	6.5	7	7
6	2.5	6	6	7	6	6.25	6
6	2.5	5	6	5	5	5.25	5
6	2.5	9	8	8	8	8.25	8
6	2.5	9	10	11	11	10.25	10
6	2.5	5.5	5	5.5	5.5	5.375	5
6	2.5	10	10	10	10	10	10
6	2.5	7	6.5	7	7	6.875	7
6	2.5	7	7	7	6.5	6.875	7
6	2.5	6	6	7	7	6.5	7
6	2.5	9.5	10	10	10	9.875	10
6	2.5	7	6	8	8	7.25	7
6	2.5	6	6	7	7	6.5	7
6	2.5	6	7	6	0	4.75	5
6	2.5	6	7	7	7	6.75	7
6	2.5	6	7	6.5	7	6.625	7
6	2.5	5	7	7	6	6.25	6
6	2.5	6	5	5	5.5	5.375	5

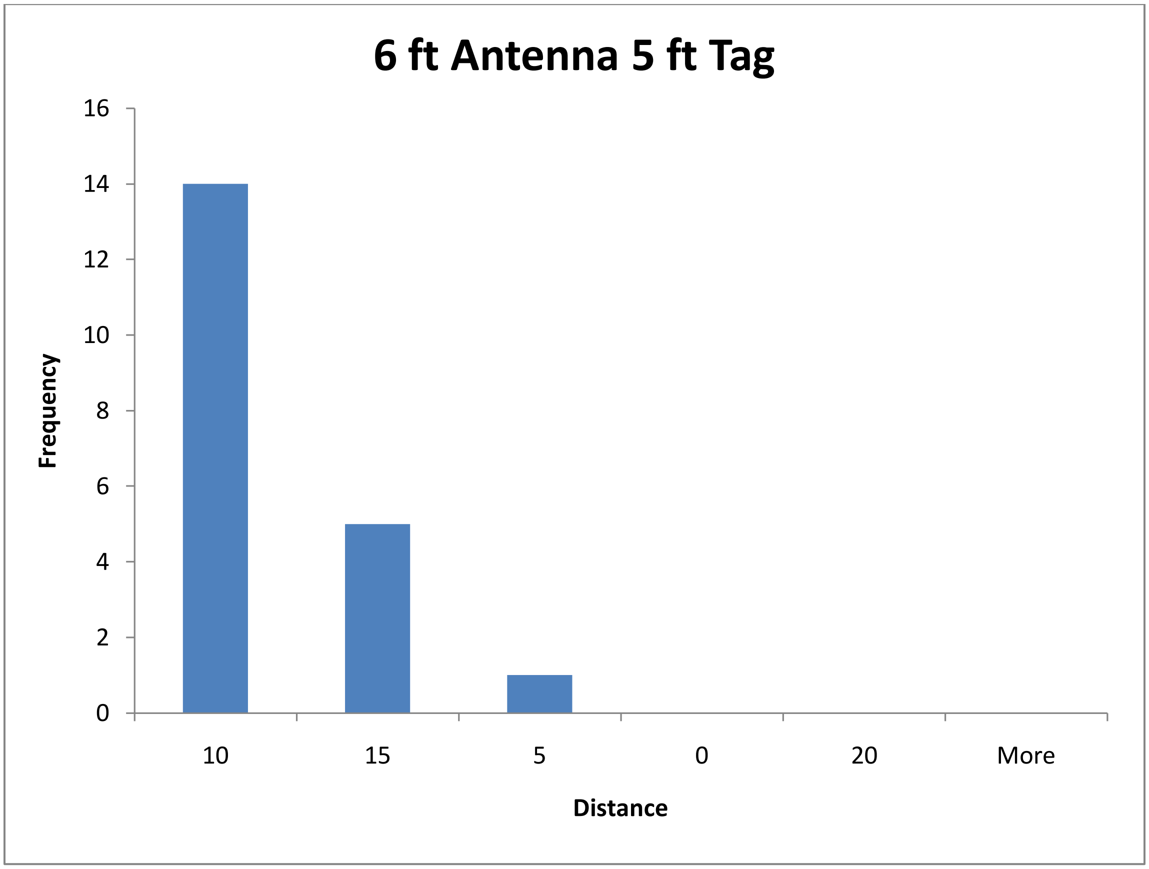
6	5	7	8	9	10	8.5	9
6	5	7	8	8	9	8	8
6	5	5	5	8	5	5.75	6
6	5	9	9	9	9	9	9
6	5	7	9	9	9	8.5	9
6	5	5	5	5	6	5.25	5
6	5	9	9	9	9	9	9
6	5	9	10	9	9	9.25	9
6	5	9	10	9	9	9.25	9
6	5	12	12	9	12	11.25	11
6	5	14	13	14	13.5	13.625	14
6	5	10	8	9	10	9.25	9
6	5	12.5	13	10	13	12.125	12
6	5	9	9	9	9	9	9
6	5	8	8.5	8	9	8.375	8
6	5	9	8.5	9	10	9.125	9
6	5	9	8.5	9	10	9.125	9
6	5	13	11	12.5	13	12.375	12
6	5	13	13	12.5	13	12.875	13
6	5	7	9	8.5	9	8.375	8

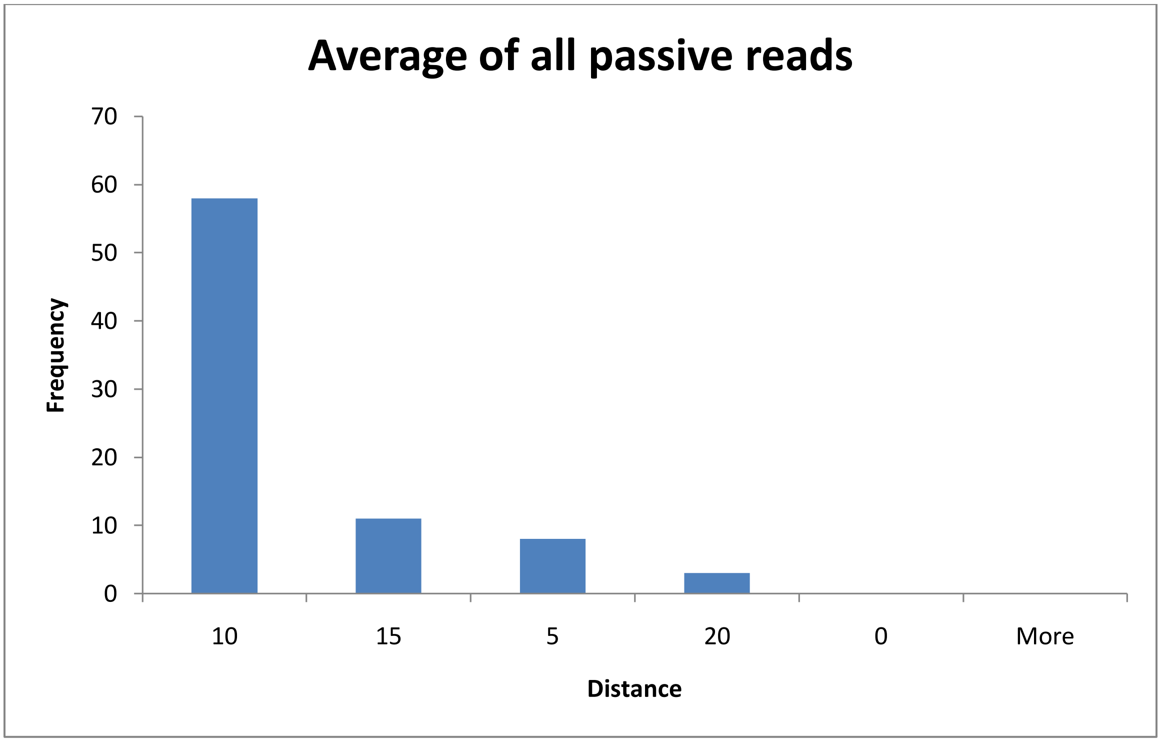
APPENDIX H HISTOGRAMS OF PASSIVE FIELD TEST




3 ft Antenna 5 ft Tag
Frequency
16
14
12
10
8
6
4
2
0
10
15
20
5
0
More
Distance


6 ft Antenna 2.5 ft Tag
16
14
12
10
8
6
4
2
0
Frequency
10
5
0
15
20
More
Distance


6 ft Antenna 5 ft Tag
Frequency
16
14
12
10
8
6
4
2
0
10
15
5
0
20
More
Distance


Average of all passive reads
Frequency
70
60
50
40
30
20
10
0
10
15
5
20
0
More
Distance

APPENDIX I ANOVA OUTPUT FOR TAG LOCATION

Tests of Between-Subjects Effects

Dependent Variable:RSSI

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1.572E7	26	604773.798	22.998	.000
Intercept	8.995E7	1	8.995E7	3420.774	.000
Location	119526.049	2	59763.025	2.273	.104
Vertical	8387650.686	2	4193825.343	159.483	.000
Horizontal	2583125.101	2	1291562.551	49.116	.000
Location * Vertical	174383.432	4	43595.858	1.658	.159
Location * Horizontal	107441.506	4	26860.377	1.021	.396
Vertical * Horizontal	4261870.558	4	1065467.640	40.518	.000
Location * Vertical * Horizontal	90121.412	8	11265.177	.428	.904
Error	9940031.600	378	26296.380		
Total	1.156E8	405			
Corrected Total	2.566E7	404			

a. R Squared = .613 (Adjusted R Squared = .586)

Pairwise Comparisons

Dependent Variable:RSSI

(I) Location	(J) Location	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a] Lower Bound	Upper Bound
	Inside	42.074*	19.738	.034	3.265	80.883
	Outside	20.407	19.738	.302	-18.402	59.217
	In-Between	-42.074*	19.738	.034	-80.883	-3.265
	Outside	-21.667	19.738	.273	-60.476	17.143
	In-Between	-20.407	19.738	.302	-59.217	18.402

Pairwise Comparisons

Dependent Variable:RSSI

(I) Vertical	(J) Vertical	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	-251.615*	19.738	.000	-290.424	-212.805
	3	-339.615*	19.738	.000	-378.424	-300.805
2	1	251.615*	19.738	.000	212.805	290.424
	3	-88.000*	19.738	.000	-126.809	-49.191
3	1	339.615*	19.738	.000	300.805	378.424
	2	88.000*	19.738	.000	49.191	126.809

Pairwise Comparisons

Dependent Variable:RSSI

(I) Horizontal	(J) Horizontal	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a] Lower Bound	Upper Bound
1	5	-187.400*	19.738	.000	-226.209	-148.591
	10	-45.096*	19.738	.023	-83.906	-6.287
5	1	187.400*	19.738	.000	148.591	226.209
	10	142.304*	19.738	.000	103.494	181.113
10	1	45.096*	19.738	.023	6.287	83.906
	5	-142.304*	19.738	.000	-181.113	-103.494

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

APPENDIX J ANOVA OUTPUT FOR READ DISTANCE

Tests of Between-Subjects Effects

Dependent Variable:Distance

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	405.969[a]	3	135.323	24.608	.000
Intercept	25382.813	1	25382.813	4615.804	.000
AntennaHeight	158.203	1	158.203	28.769	.000
Tagheight	189.112	1	189.112	34.390	.000
AntennaHeight * Tagheight	58.653	1	58.653	10.666	.001
Error	1737.719	316	5.499		
Total	27526.500	320			
Corrected Total	2143.687	319			

a. R Squared = .189 (Adjusted R Squared = .182)

Pairwise Comparisons

Dependent Variable:Distance

(I) AntennaHeight	(J) AntennaHeight	Mean Difference (I-J)	Std. Error	Sig.[a]
3	6	1.406*	.262	.000
6	3	-1.406*	.262	.000

Univariate Tests

Dependent Variable:Distance

	Sum of Squares	df	Mean Square	F	Sig.
Contrast	158.203	1	158.203	28.769	.000
Error	1737.719	316	5.499		

The F tests the effect of AntennaHeight. This test is based on the linearly independent pairwise comparisons among the estimated marginal means.

Pairwise Comparisons

Dependent Variable:Distance

(I) Tagheight	(J) Tagheight	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
2.5	5.0	-1.538*	.262	.000	-2.053	-1.022
5.0	2.5	1.538*	.262	.000	1.022	2.053

Based on estimated marginal means

*. The mean difference is significant at the .05 level.