Assessment of Montana Road Weather Information System

Task 2- State of the Art Review

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1) INTRODUCTION

Road weather information systems (RWIS) are networks of weather sensors used by transportation agencies to monitor weather occurring on the roads they maintain. The earliest instances of RWIS deployment are documented in the 1970s and those early deployments were mainly focused on providing information to assist with winter road maintenance (PB & Iteris, 2013a). RWIS programs have expanded from their initial focus to include a broader set of stakeholders and data users as well as new and more diverse technologies. RWIS programs now regularly serve not only DOT maintenance personnel, but traveler information personnel, operations personnel, advanced intelligent transportation system (ITS) applications, the travelling public, and third-party service providers.

Today most environmental sensor stations (ESS) for RWIS typically include various atmospheric sensors, some form of pavement sensor, and camera imaging. Additional sensors are also being added to some ESS locations to measure traffic volumes, traffic speeds, and vehicle classifications and weights (Hawkins & Albrecht, 2014). Mobile sensors are also being utilized by many agencies to measure road and atmospheric conditions in real-time attached to maintenance vehicles. Each of these sensor combinations allow for different end user benefits as shown in Figure 1.

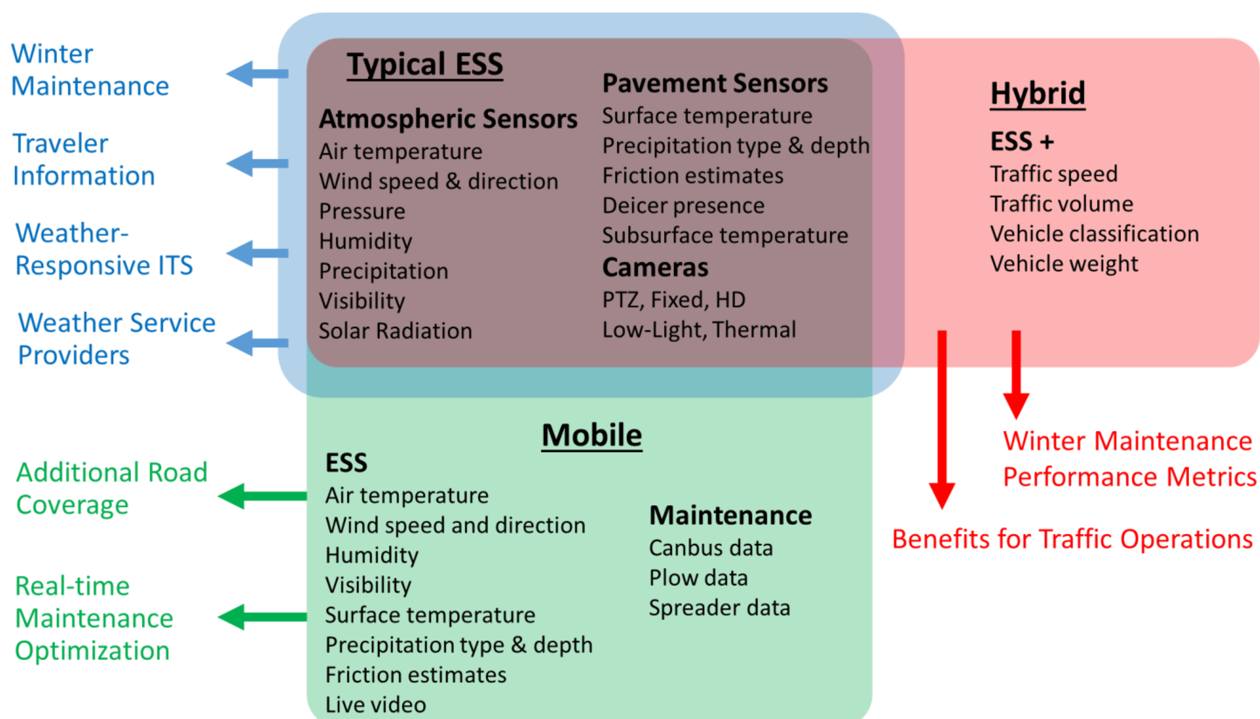

Figure 1: RWIS Components and Uses

RWIS networks also allow for maintenance decision support systems (MDSS) which assist winter maintenance personnel in performing winter ice and snow clearing operations. Pavement condition forecasting efforts have also been advanced to assist practitioners by providing likely pavement surface conditions given the observed and forecast weather patterns, maintenance activities, and traffic (Feng & Fu, 2014).

What started as an efficient means for DOT maintenance personnel to monitor weather remotely and react accordingly has grown to be valued by other interests and as a result the technologies employed by traditional RWIS have been added to and adjusted. This report will review all literature pertaining to RWIS, focusing on data adequacy and reliability, picture and video technologies, geographic coverage, and benefit-cost analyses both for the primary stakeholder, DOT maintenance staff, as well as the additional end users.

2) RWIS LITERATURE

The use of RWIS has been studied and evaluated a number of times over the past 30 years as the practice has evolved. Today new technologies emerge rapidly resulting in expanding RWIS capabilities and possibilities. The following sections will provide details of the documented RWIS literature with emphasis on the most recent knowledge and technological capabilities.

2.1. Data Adequacy and Reliability

Data adequacy and reliability are dependent upon the intended uses of the sensor measurements. For instance, adequate data for traditional winter maintenance uses may be different than adequate data for releasing to the travelling public or monitoring the traffic impacts of winter storms. Similarly the different uses of RWIS data can require different levels of reliability; e.g. a weather-responsive variable speed limit sign may require higher reliability than general traveler information. In general, high reliability has been considered paramount to the success of an RWIS program, and high reliability is often dependent on system maintenance, training and dependable communications (Abdi et al., 2012, Ballard et al., 2002, Battelle, 2006 and Boon & Cluett, 2002). General accuracy and reliability concerns were uncovered occasionally during this review, however, specific figures relating to accuracy and reliability are not typically found in the unbiased literature. The following subsections detail the types of data acquired from each of the various types of sensors and any information uncovered regarding their typical accuracy and/or reliability.

The reader should be mindful that sensor capabilities and technologies are often only available from manufacturer sources, so the following sections do identify sensor producers and general producer information, but use no quality or reliability conclusions based on manufacturer information. Any and all documented statements of quality or reliability stem only from previously published unbiased evaluations and studies.

Many manufacturers and vendors produce atmospheric and pavement weather sensors capable for use in RWIS applications. A handful of companies seem to be aimed at providing comprehensive RWIS sensor packages, while many other companies are focused on providing one or a few technologies that may then be part of larger RWIS packages. Companies that could be identified as providing comprehensive packages of RWIS sensors (including both atmospheric and pavement sensors) in the US are shown in Table 1.

Table 1: Comprehensive RWIS Providers in the US

Producer	Nearest Location	Atmospheric Sensors							Pavement Sensors	
		Air Temp.	Humidity	Pressure	Solar Rad.	Visibility	Wind	Precip.	In-Pave.	Non-Inv.
Aanderaa Data Instruments	Massachusetts	X	X	X	X	X	X	X	X	
All Weather Inc.	California	X	X	X	X	X	X	X	X	
Boschung	Colorado	X	X	X	X	X	X	X	X	
Geonica via Advanced Monitoring Methods	Colorado	X	X	X	X	X	X	X	X	X
High Sierra Electronics	Utah	X	X	X	X	X	X	X	X	X
Lufft	California	X	X	X	X	X	X	X	X	X
Vaisala	Colorado	X	X	X	X	X	X	X	X	X

(list compiled with assistance from databases maintained by The Association of Hydro-Meteorological Equipment Industry (HMEI) website at hmei.org and meteo-technology.com)

While these RWIS providers typically manufacture some of their own sensors, it is not uncommon to see re-branded sensors that may come from other sources. Table 2 shows a sample of identifiable weather sensor providers (both US and International) and the technologies they offer either themselves or indirectly through the comprehensive RWIS providers.

Table 2: Weather Sensor Providers

Producer	**Sensors**
Belfort Instrument (belfortinstrument.com)	Full suite of atmospheric sensors
Biral (biral.com)	Full suite of atmospheric sensors
Cimel (camel.fr)	Full suite of atmospheric sensors
Climatronics (climatronics.com)	Full suite of atmospheric sensors
Coastal Env. Syst.s (coastalenvironmental.com)	Full suite of atmospheric sensors
Envirotech Sensors (envirotechsensors.com)	Visibility sensors
Eppley Laboratory (eppleylab.com)	Solar radiation sensors
Kipp and Zonen (kippzonen.com)	Solar radiation sensors
Logotronic (logotronic.at)	Full suite of atmospheric sensors
Met One Instruments (metone.com)	Full suite of atmospheric sensors
NovaLynx (novalynx.com)	Full suite of atmospheric sensors
Optical Scientific (opticalscientific.com)	Full suite of atmospheric sensors
Paroscientific (paroscientific.com)	Air temperature, humidity and pressure sensors
Pulsonic (pulsonic.net)	Full suite of atmospheric sensors
RM Young (youngusa.com)	Full suite of atmospheric sensors
Rotronic (rotronic-usa.com)	Air temperature, humidity and pressure sensors
Sensice (sensice.com)	Non-invasive road surface sensors
Setra (setra.com)	Air temperature, humidity and pressure sensors
Sterela (sterela.fr)	Full atmospheric (unknown pavement sensors)
Sutron (sutron.com)	Full suite of atmospheric sensors
Texas Electronics (texaselectronics.com)	Full suite of atmospheric sensors
Yankee Env. Systems (yesinc.com)	Full suite of atmospheric sensors

(list compiled with assistance from databases maintained by The Association of Hydro-Meteorological Equipment Industry (HMEI) website at hmei.org and meteo-technology.com)

2.1.1. Atmospheric and Pavement Sensors

Most atmospheric and pavement sensor types have been used for some time now. Many of the attributes measured by atmospheric and pavement sensors (air temperature, pavement temperature, wind speed & direction, precipitation type, and humidity) have been found to be among the most accurate and reliable of all road weather characteristics examined by a national survey of surface transportation personnel (Hart et al., 2009).

<u>Air Temperature, Humidity, and Barometric Pressure</u>

Air temperature, humidity and barometric pressure sensors can be individual sensors or be part of clustered sensors that can measure many attributes. Most installations utilize air temperature and humidity together to calculate a dew point temperature. Figure 2 shows some typical temperature, humidity, and pressure sensors with an air temperature only sensor (left), air temperature and humidity sensor (center), and an air temperature, humidity, pressure, solar radiation, and wind speed and direction sensor cluster (right).

Figure 2: Air Temperature, Humidity and Barometric Pressure Sensors

No relevant reliability concerns were identified regarding the use of these air temperature, humidity, and barometric pressure sensors for RWIS applications.

<u>Solar Radiation</u>

Solar radiation sensors, also known as pyranometers, can be part of clustered sensors as shown in Figure 2 (far right) or be individual sensors like those shown in Figure 3.

Figure 3: Solar Radiation Sensors

No relevant reliability issues were identified regarding the use of these solar radiation sensors for RWIS applications.

<u>Visibility</u>

Visibility sensors are available in a few different designs and can be standalone sensors, or be integrated into weather sensors that measure both visibility and precipitation data. Figure 4 shows different visibility sensors with a standalone sensor (left) and visibility with precipitation sensors (center and right).

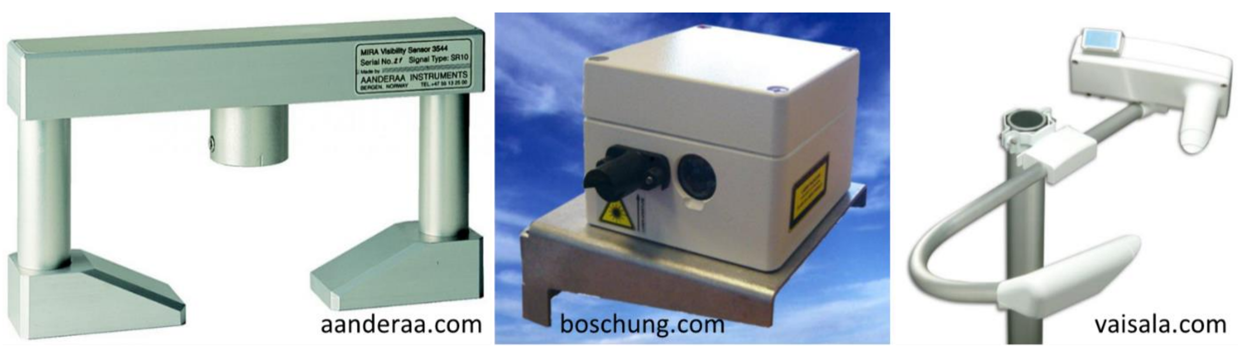

Figure 4: Visibility Sensors

Documented issues regarding these sensors include:

- Visibility and precipitation sensors that utilize optical sensing methods are susceptible to lens cleaning requirements as winter road slush and debris can cause problems if the sensing lens becomes obstructed (PB & Iteris, 2013b).
- In one documented instance backscatter visibility sensor technology was found to be unreliable and replaced with forward-scatter visibility sensors (Murphy et al., 2012).

Wind

Wind sensors that measure wind speed and direction are typically either mechanical (anemometer and vane) or ultrasonic sensors (with no moving parts). Ultrasonic wind sensors can be standalone or part of clustered sensors like that shown in Figure 2 (far right). Figure 5 shows some of the standalone wind speed and direction sensor types available.

Figure 5: Wind Sensors

Mechanical wind sensors were the only option for some time and performed adequately, but remain susceptible to icing problems and require regular maintenance especially on bearings. The low maintenance ultrasonic wind sensors are becoming more popular, evidenced by agencies like Michigan DOT who are exclusively using ultrasonic wind sensors on all new RWIS deployments (Hoch et al., 2006 and PB & Iteris, 2013b).

Precipitation

Atmospheric precipitation sensors also come in a variety of forms with some being mechanical (tipping bucket type) to measure precipitation rate, and others using optical, infrared, or radar technologies to determine precipitation type and intensity. Figure 6 shows the types of atmospheric precipitation sensors available from RWIS vendors.

Figure 6: Precipitation Sensors

Documented issues regarding these sensors include:

- Again, visibility and precipitation sensors that utilize optical sensing methods are susceptible to lens cleaning requirements as winter road slush and debris can cause problems if the sensing lens becomes obstructed (PB & Iteris, 2013b).
- High winds can also cause optical type precipitation sensors to overestimate precipitation rates (PB & Iteris, 2013b).

In-Pavement

Sensors embedded into the road surface are used to determine pavement temperature, subsurface temperature, and road surface conditions such as deicer presence, freeze temperature, precipitation presence and depth, and friction estimates. These sensors can measure one or a number of these attributes depending on the model. Figure 7 shows four in-pavement sensors from different RWIS vendors.

Figure 7: In-Pavement Sensors

Documented issues regarding these sensors include:

- Past work has documented pavement temperature sensor reliability and accuracy issues (Ballard et al., 2002 and STWRC, 2009). Note: these issues are somewhat dated, so the causes for the problems may since have been addressed by the manufacturer or agency personnel.
- In one study, the "chemical presence and concentration detectors [were] notoriously unreliable" (Boon & Cluett, 2002). Concern was also voiced about these chemical concentration sensors by Zwahlen et al. (2003). Again note: these concerns are dated now, and may or may not have been improved. They could also be related to the fact that certain sensors are calibrated for specific deicing chemicals only (Mitchell et al., 2006).

Non-Invasive

Non-invasive pavement sensors are installed above the roadway either on a gantry or pole near the roadside. This more recent sensor technology has been evaluated and been found to be generally reliable for many transportation applications (Ewan et al., 2013). Non-invasive pavement sensors utilize infrared technology to determine road temperature and surface conditions like precipitation presence, type and depth, and a road surface friction estimate.

Figure 8: Non-Invasive Pavement Sensors

Documented issues regarding these sensors include:

- These non-invasive road weather sensors have a maximum measuring distance to the road surface. This maximum distance is often less than what many existing ESS tower installation would allow, and as such may require an additional mounting platform to be used (PB & Iteris, 2013b).
- The accuracy of the measurement of precipitation depth can be dependent on sensor installation angle for some non-invasive pavement sensors, therefore special considerations may be required for installation mounting geometries (Al-Kaisy et. al., 2012).

2.1.2. Camera Technologies

Camera technologies and remote monitoring have evolved since the emergence of RWIS programs and it is becoming increasingly common to have cameras at most ESS locations. As of 2007 there were over 10,000 cameras continuously monitoring major roadways in the US (Hallowell et al., 2007). Image processing is now possible on site and this coupled with network communications has made additional camera uses besides just live video monitoring a possibility. While not necessary for most RWIS applications, new camera capabilities like vehicle counting, vehicle classification, license plate recognition, and automated incident detection are possible (Axis, 2014). High definition, thermal imaging, and low-light technologies are recent advances that can improve the overall capabilities of transportation infrastructure monitoring (Mobotix, 2015). Tradeoffs between camera functionality, image quality and data transfer can dictate what cameras are used for at ESS locations. Cameras can be fixed and constantly aimed at one viewing area or be pan-tilt-zoom (PTZ) type that allow for remote control to change the viewing area and zoom level. A sample of some comprehensive camera providers that serve the transportation sector include:

- Adventura Technologies (aventuracctv.com)
- Arecont Vision (arecontvision.com)
- Axis Communications (axis.com)
- CohuHD (cohuhd.com)
- Infinova (infinova.com)
- Mobotix (mobotix.com)
- Pelco / Schneider Electric (pelco.com)
- Siqura (siqura.com)
- Vicon - including recently acquired IQinVision (vicon-security.com)
- Wireless Technology Inc. (gotowti.com)

Regardless of the type of cameras used, the communication technology can also influence the quality and capabilities of the imaging. Internet Protocol (IP) network cameras are becoming more common and may offer some advantages over analog cameras especially in remote locations where agencies may desire still images to be transferred at regular time intervals (Duplack, 2015). As a technology, IP network cameras may allow for certain capabilities not available with analog cameras including potentially better image quality, single cable to transfer data / power / PTZ controls, and on-site video image processing (Axis, 2009). See Appendix A for schematic designs highlighting the power and communication differences for IP network and analog cameras.

Documented issues regarding cameras at ESS locations include:

- Low-light situations can render some camera images useless, therefore it is advisable to use cameras that include technologies that allow for functionality in low light conditions (PB & Iteris, 2013a).
- Mounting structures effected by wind or vibrations can cause poor image quality (McGowen, 2008).

2.1.3. Mobile Sensors

Mobile sensors are a more recent technology to be integrated into RWIS. Currently mobile road weather sensors are capable of measuring road temperature and surface conditions such as precipitation type and depth as well as surface friction estimate and ambient air temperature and humidity. Mobile road weather sensors have unique communications challenges but can allow for valuable benefits like real-time winter maintenance optimization, additional RWIS geographic coverage, and operational data related to winter storm clearance and safety improvements (Lapointe, 2011). Additional information regarding the current use of and future outlook for mobile RWIS is expected to be gleaned from surveys in *Task 3: State of Practice*. Figure 9 shows the mobile road weather sensors available from the RWIS providers.

Figure 9: Mobile Sensors

One issue regarding mobile sensors was stated: “mobile sensor systems have performed well when attached to light-duty vehicles, but struggle in the harsh environment that surrounds snowplows during plowing operations” (PB & Iteris, 2013b).

2.1.4. General Issues Identified

Overall, most of the reliability concerns with RWIS data stem from earlier evaluations and instances with DOT personnel that may not have had adequate experience with RWIS equipment. This may also have been exacerbated by poor maintenance programs, training practices and/or unfamiliar sensor technologies. Today RWIS data seems to be more reliable and more trusted by agency personnel than before, but general reliability concerns continue to be sparsely documented.

Documented issues regarding RWIS overall (with no specific sensor type identified) include:

- A recent survey of 37 RWIS personnel in New York found that about 30% of respondents were dissatisfied with the reliability of RWIS equipment and data transmission (Chien et al., 2014).
- Certain RWIS equipment power supplies have also been documented to have issues in very cold temperatures (ITS Int., 2013).
- In general, maintenance and knowledgeable technicians go a long way toward ensuring reliable sensor outputs, and as such many DOTs are choosing to solve data reliability issues by contracting to a service vendor with performance contracts that ensure certain levels of accuracy and reliability without having to train their own personnel (PB & Iteris, 2013a).
- Proprietary system architecture designs can be limiting and therefore open ESS system architecture designs are now desired by many agencies to allow for flexibility and inclusion of sensors and technologies from multiple producers (Ballard et al., 2002, Battelle, 2006, PB & Iteris, 2013a, and STWRC, 2009,).

2.2. Geographic Coverage

RWIS programs have continued to expand geographically in many states over the past decade. States that face significant winter weather challenges like Montana typically have extensive networks of ESS. Table 3 shows the number of ESS and approximate coverage characteristics for states that experience significant winter weather.

Table 3: ESS by State

State	Number of ESS	Land Area (sq. mi)	Select Road Miles	Approx. Road Miles Covered per ESS	Approx. Land Area Coverage Radius (miles) per ESS
MT	72	145,546	4,180	58	25
CO	150	103,642	4,462	30	15
ID	125	82,643	2,572	21	15
IA	96	55,857	5,020	52	14
MI	66	56,539	5,257	80	17
MN	95	79,627	5,217	55	16
NY	45	47,126	5,665	126	18
ND	26	69,001	3,645	140	29
OH	172	40,861	5,634	33	9
OR	71	95,988	4,077	57	21
SD	46	75,811	3,679	80	23
UT	83	82,170	2,740	33	18
WA	120	66,456	3,559	30	13
WI	59	54,158	5,523	94	17
WY	82	97,093	3,055	37	19

Select Road Miles from USDOT Highway Statistics 2013 including Interstates, freeways, and principal arterials. Land Area from census.gov. Number of ESS from FHWA National ESS Map: (ops.fhwa.dot.gov/weather/mitigating_impacts/essmap.htm), individual state DOT websites, (Hawkins & Albrecht, 2014), or (PB & Iteris, 2013a).

ESS alone can provide valuable information for local uses, but once certain levels of geographic coverage are reached additional area wide forecast benefits can be realized. If located properly, ESS can serve both local and larger regional needs (Manfredi et al., 2008). The quality of data and level of benefits realized by having a large network of ESS is dependent on the geographic placement of the stations. Perhaps the most common and traditional method for geographic ESS placement has been to rely on local expertise including knowledge from maintenance personnel and meteorologists (Ballard et al., 2002, Kwon and Fu, 2014 and Manfedi et al., 2008). In addition to local expertise, logistical concerns have also dictated ESS placement practices especially in remote locations: logistical concerns like the presence of power and communications and the proximity to maintenance shops such that routine maintenance can be performed in a single day (Hoch et al., 2006, McGowen, 2008, and Zwahlen et al., 2003).

2.2.1. General Guidance

The most recent FHWA ESS Siting Guidelines (Manfedi et al., 2008) provide details concerning local siting, but little specific guidance for macro-scale geographic ESS placement beyond relying on DOT personnel and meteorologists. In general, the authors state that the placement of regional ESS should be on relatively flat, open terrain on the upwind side of the road.

Zwahlen et al. (2003) have identified many additional factors to consider when determining the placement of ESS including: climactic history, road class, traffic volumes, locations with high grades, crash history, and common storm pattern movement directions. While these factors are listed, a method for using them for geographic placement is not described in the report.

Researchers in North Dakota (STWRC, 2009) determined that a 30 mile radius coverage area should not be exceeded in order to discern finer scale weather patterns given North Dakota's land-use and terrain. This is in-line with the FHWA guidelines recommendation of up to 20 to 30 miles for regional ESS (Manfedi et al., 2008). Using this general guideline and the existing ESS network, the researchers provided 18 additional recommended ESS locations to ensure more comprehensive coverage. Figure 10 shows the existing (brown) and proposed supplemental (blue) ESS stations and their 15 and 30-mile coverage radii.

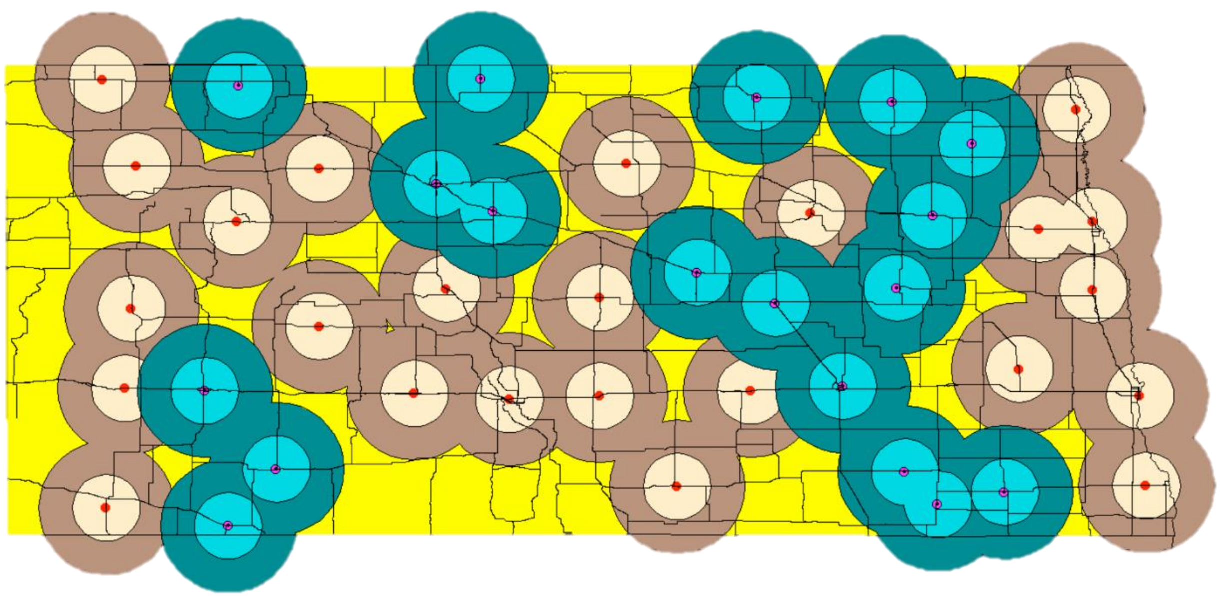

Figure 10: ESS Supplement Plans for North Dakota (STWRC, 2009)

2.2.2. Systematic Approaches

Efforts in recent years have attempted to develop citing procedures that involve somewhat more objective and analytical means to determine geographic ESS placement. Analyzing the potential placement of 10 ESS in the Austin Texas region, Jin et al. (2013) developed a placement optimization model that was driven primarily by weather-related crash history. The authors developed a safety concern index based on past weather related crash occurrence then spatially optimized the placement of the 10 ESS to obtain the greatest risk coverage assuming a 10 mile area coverage radius per ESS. Figure 11 shows the optimized ESS placement plans for different crash analysis years.

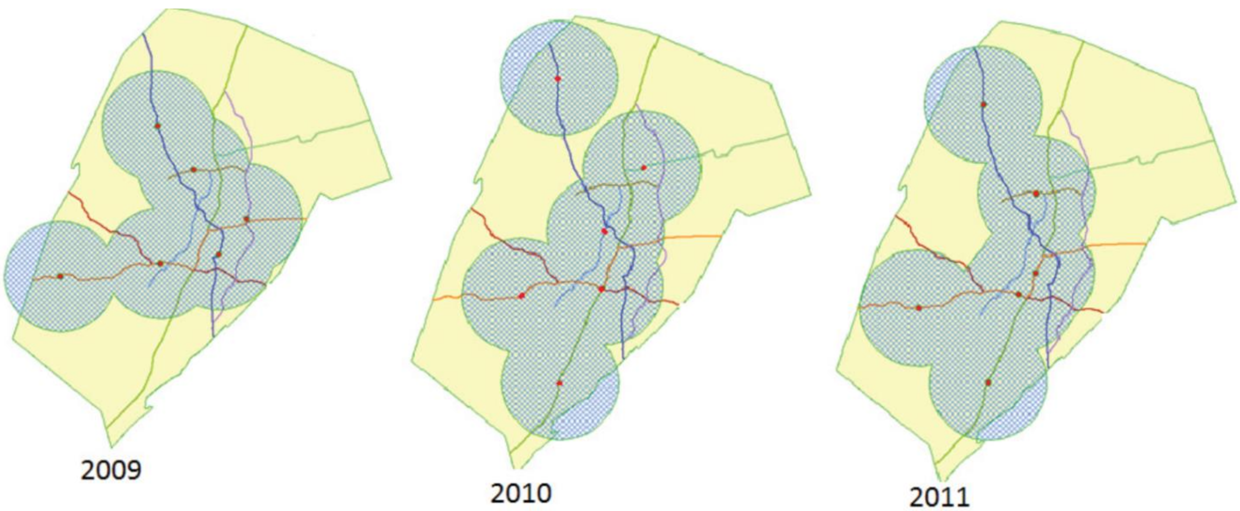

Figure 11: ESS Placement Optimization Models for Austin Area (Jin, et. al., 2013)

During the initial design (Pinet & Lo, 2003) of Alberta's RWIS network and a later expansion (Pinet & Bielkiewicz, 2009) the authors described the geographic siting procedures considering many factors. Topography, hydrology, meteorological zones, winter crash statistics, traffic volumes and expertise from local meteorologist helped define influence areas for each ESS as well as the overall placement of the RWIS network. The initial RWIS locations were limited to the National Highway System and the expansion designs branched out from the initial placements. Figure 12 shows the initial placement design (left) with the approximate coverage areas and the expansion design (right).

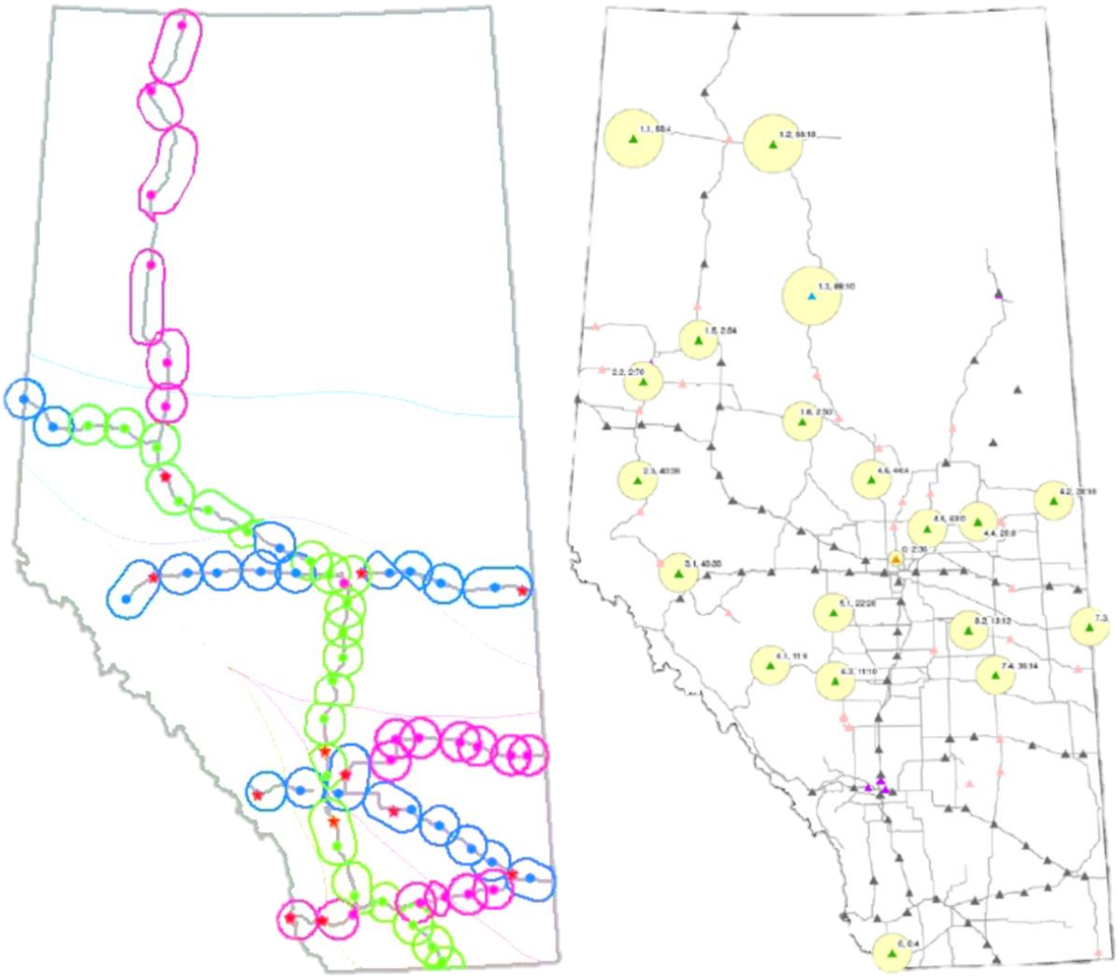

Figure 12: ESS Placement Plans for Alberta (Pinet & Bielkiewicz, 2009)

Kwon and Fu (2014) developed geographic ESS placement methods based on multiple factors including surface temperature variability, mean surface temperatures, precipitation amounts, traffic volumes, crash rates, and highway classification. The authors also investigated case studies of their methods using different combinations of the placement factors for Ontario, Canada. The study area was first broken into equal sized cells for analysis, next only cells containing the relevant road network were considered as candidates for ESS placement, and then the analyses using the factors above were performed resulting in the candidate locations. Figure 13 shows one of the placement models with the highest 140 ranked candidate locations highlighted and grid shading according to the prioritization from a combination of all factors.

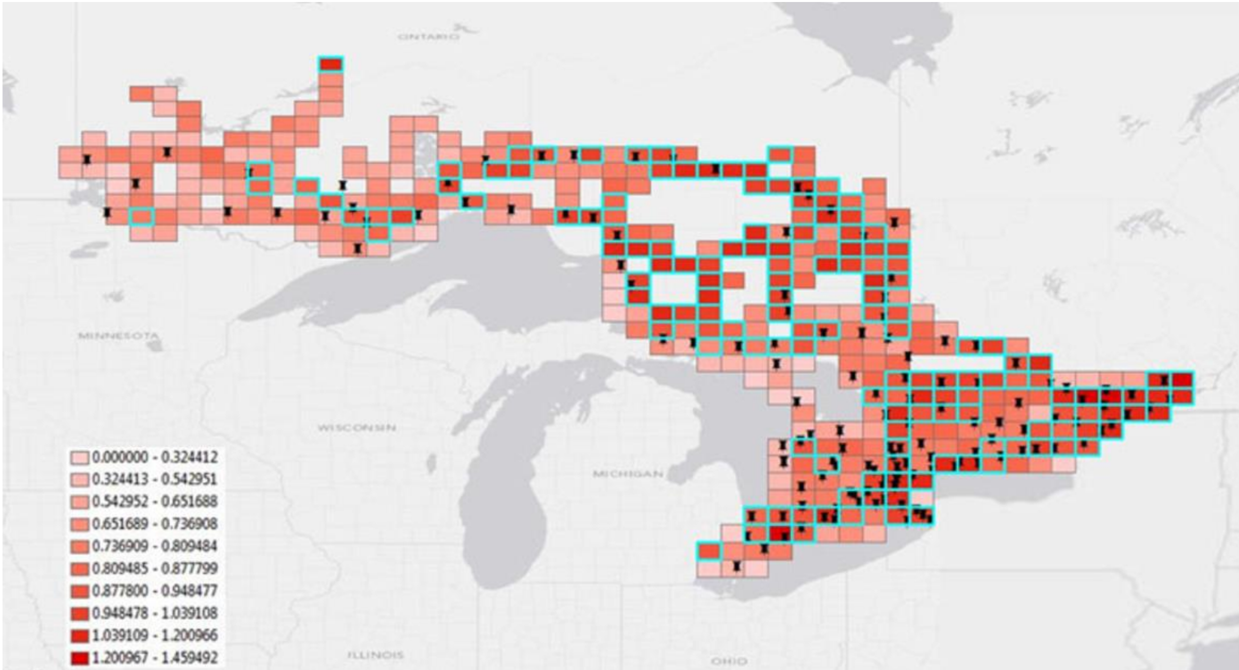

Figure 13: ESS Placement Model for Ontario (Kwon and Fu, 2014)

Yang and Regan (2014) developed a methodology to prioritize the placement of ESS for RWIS in South Korea. Their methods for prioritizing placement of ESS includes factors related to snow vulnerability analysis, winter crash statistics, traffic volumes, and the presence of nearby cameras. The initial areas prone to snow were identified by personnel in regional offices and additional snow vulnerability analysis was performed on these areas. Next, these areas were reduced to eliminate places that already had ESS or nearby automatic weather stations (AWS) that were placed appropriately to provide ESS type road weather information. Finally, the remaining areas were prioritized by considering winter crash history, traffic volumes, and whether or not a camera was installed nearby.

2.3. Benefit – Cost Relationships

Weather causes significant challenges for transportation agencies. The economic impact of weather related crashes tops $42 billion each year and transportation agencies spend another $2 billion on snow and ice removal (FHWA-RITA, 2010). RWIS programs do offer many benefits to try to mitigate these costs. A considerable number of benefit cost analyses for RWIS have been reported in the published literature. These analyses often consider different components when determining a benefit to cost ratio. Recently FHWA published a Road Weather Benefit Cost Analysis Compendium which reviews some past efforts and provides tools to help practitioners perform future benefit-cost analyses (Lawrence et al., 2014). Different analyses consider different costs and different benefits be they agency specific benefits or societal benefits.

Typical RWIS costs considered can include (Boselly, 2002, Fay et al., 2010, and Lawrence et al., 2014):

- Design / Engineering
- Land acquisition
- Construction / Installation
- Sensors / Equipment
- Power
- Communications
- Training
- Maintenance
- 3rd Party Services

Typical RWIS benefits considered can include (Boselly, 2002, Fay et al., 2010, and Lawrence et al., 2014):

Agency Specific

- Materials: less winter maintenance materials used
- Labor: less personnel hours needed
- Equipment: reduced equipment wear

Societal

- Safety: fewer and/or less severe crashes
- Operations: improved travel times, reduced delay, improved level of service
- Travel Information: improved and timely information for travelers
- Infrastructure: less wear on roads, bridges, guardrail
- Environmental: less fuel consumption, less impact to roadside environment

Many of the benefit-cost studies documented are prepared assuming some aspects of the program costs and benefits to develop anticipated benefit-to-cost (B:C) ratios prior to deployment. Some analyses attempt to capture actual post-deployment costs and benefits, but assigning clear cause and affect relationships from RWIS deployments is not always definitively possible. Table 4 shows the documented studies that published benefit-cost relationships as well as the factors considered and whether the analysis was anticipated (pre-deployment) or post-deployment.

Table 4: Benefit – Cost Studies

Location (Reference)	Costs	Benefits		B:C Ratio
		Agency Specific	**Societal**	
Alberta, Canada (AIT, 2006)	Undefined	Materials Labor	Safety	5.4 : 1 (anticipated)
Washington (Boon & Cluett, 2002)	Undefined	Materials Labor		5 : 1 (anticipated)
Colorado (Boselly, 2002)	Equipment 3rd Party Services	Materials Labor Equipment		1.1 : 1
Wisconsin (CRC, 2002)	Undefined	Materials Labor	Safety	5 : 1 to 15 : 1
New York (Chien et al., 2014)	Design Installation Equipment Power Communications Maintenance	Materials Labor Equipment	Safety Operations Infrastructure Environmental	10 : 1 to 15 : 1 (anticipated)
Idaho (Koeberlein et al., 2015)	Undefined		Safety	22 : 1
Utah (Strong and Shi, 2008)	Undefined	Materials Labor		11:1
Iowa (Veneziano et al., 2014)	Installation Equipment Power Communications Training Maintenance 3rd Party Services	Materials Labor Equipment		3.8 : 1
Iowa (Veneziano et al., 2014)	Installation Equipment Power Communications Training Maintenance 3rd Party Services	Materials Labor Equipment	Safety	45 : 1
Iowa (Ye et al., 2009a)	Maintenance 3rd Party Services	Materials Labor Equipment		1.8 : 1
Nevada (Ye et al., 2009b)	Maintenance 3rd Party Services	Materials Labor Equipment		3.2 : 1
Michigan (Krechmer et al., 2008)	Installation Equipment Maintenance	Materials Labor	Safety Operations	2.8 : 1 to 7 : 1

From the documented RWIS benefit-cost studies, it follows that agency specific benefit cost ratios range from 1.1:1 to 11:1 and overall benefit cost ratios (including societal benefits) range from approximately 3:1 to 45:1 depending on the factors considered. Regardless of the methods used, there seems to be a consensus that, in general, RWIS benefits outweigh the costs and particularly so when societal costs are considered besides agency costs.

3) SUMMARY

RWIS programs have evolved from their original intent, but remain focused primarily on winter maintenance and safety benefits. New technologies and capabilities have also contributed to RWIS serving many end users for different purposes including traditional winter maintenance, traveler information, operations activities, advanced ITS applications, and third-party weather service providers.

Many sensor technologies exist that are aimed at providing road weather observations. Most of these technologies have been used successfully for some time now, but proper maintenance and reliable communications are a must to ensure quality and timely data. Certain considerations for specific sensor technologies documented in past works can guide new acquisitions and maintenance practices. Newer mobile sensor technologies hold promise for future applications. Where there once was only one major RWIS vendor, there are now multiple providers which allows for multiple technology sources. Open architecture type systems are more flexible and are often desired now more than ever by transportation agencies. Additional insight into system architectures and software platforms is anticipated in *Task 5: Weather Data and Software Analysis*.

States faced with winter challenges typically have large networks of ESS to ensure considerable coverage of the roads they are tasked with maintaining. In the past only general guidance on geographic ESS placement was available and it consisted mostly of relying on local expertise from agency personnel and meteorologists. More recent efforts have begun to define systematic, objective ESS placement methods that attempt to quantify and optimize the knowledge traditionally held by agency personnel. Optimization models using data related to winter crash history, traffic volumes, and historical climate data are now being proposed.

Overall, RWIS programs have produced many benefits that typically outweigh the cost considerably. Transportation agency specific benefits like labor, materials, and equipment cost savings have benefit-to-cost ratios ranging from 1.1:1 up to 11:1. When safety, operational, and other societal benefits are also considered the benefit-to-cost ratio increases and can exceed 40:1. The knowledge gained form the procedures used in these benefit cost analyses will be valuable for *Task 6: Benefit Cost Analysis*.

The knowledge gained from this literature review will be added to that obtained during *Task 3: State of Practice Review*, where transportation agency personnel from peer states share their knowledge and experience with RWIS systems. A few recent state of practice reviews were discovered during this literature review and will be valuable for *Task 3* to ensure that previously documented insights from recent surveys are not re-hashed. Similarly, the knowledge gained from this literature review will assist in *Task 4: Needs Assessment*, where all potential Montana DOT stakeholders and needs are explored.

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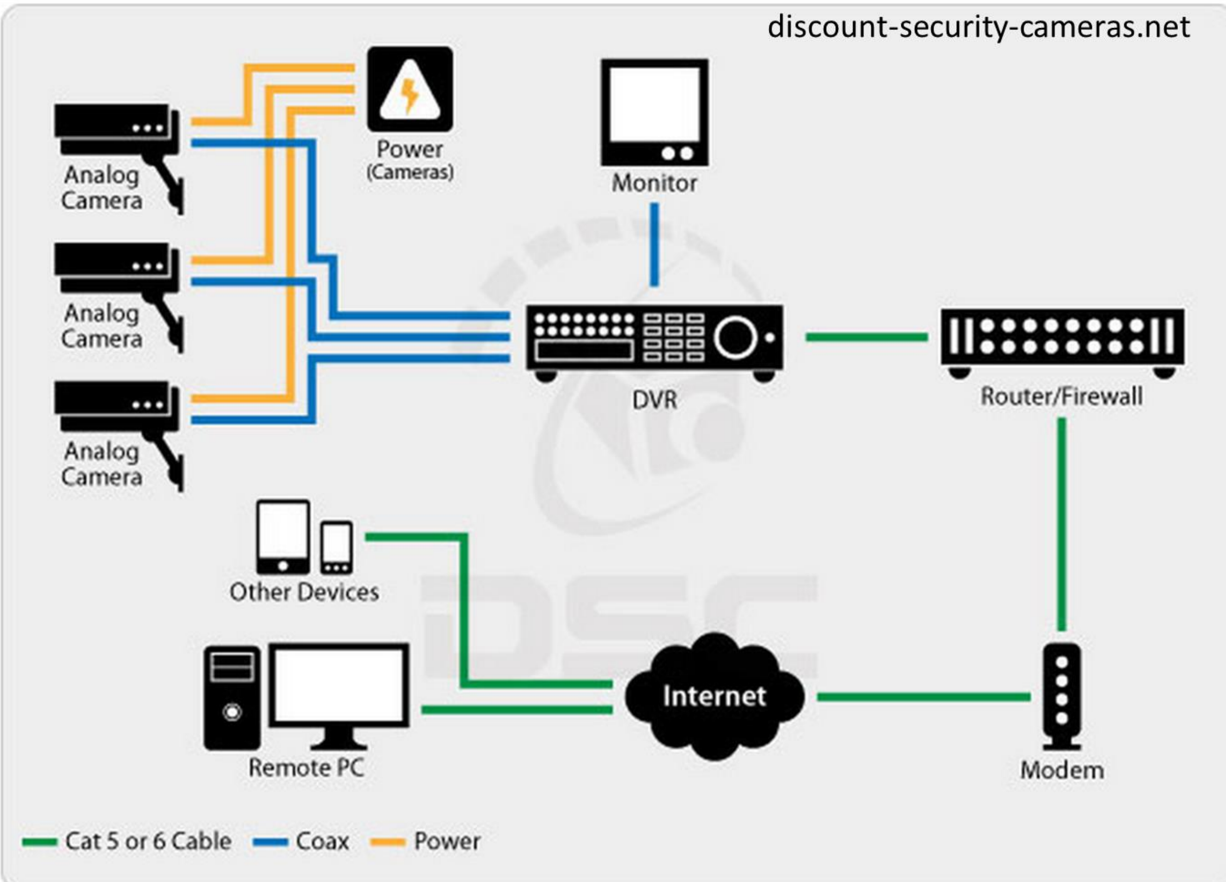
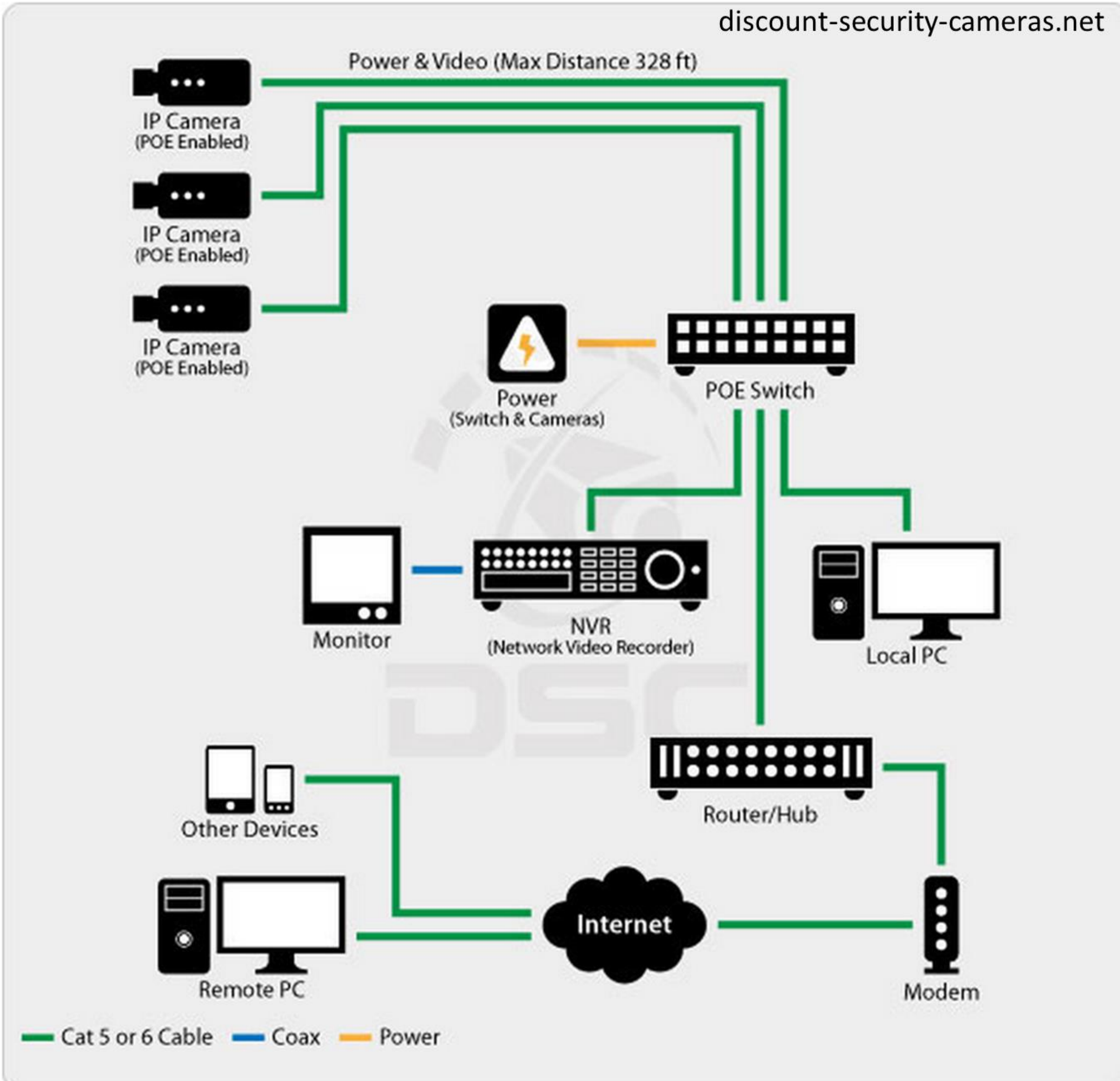
5) APPENDIX A

Analog Camera System Design Schematic (from discount-security-cameras.net)



IP Network Camera System Design Schematic (from discount-security-cameras.net)



IP + Wireless Network Camera System Design Schematic (from discount-security-cameras.net)