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Use of Mobile Sensors and Maintenance Decision Support for Automated Road Condition Reporting

Final Report Submitted to:

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and
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1. INTRODUCTION

Department of transportation (DOT) maintenance personnel and State Highway Patrol (SHP) officers have provided road condition reports for over 60 years. Colorado DOT was routinely collecting field observations made by plow drivers and patrolling supervisors via radio in the mid-1950s (Gordon Bell, personal communication). This information was collected by the SHP and manually recorded and made available via a phone number open to the public. The road condition reports contained observations/assessments of the surface state of the highway and weather conditions impacting travel. Although the methodology of collecting, consolidating, and disseminating road condition reports has changed over time as new data processing and communications capabilities have evolved, the fundamental road condition reporting process existing in the 1950s persists to this date.

2. CURRENT ROAD CONDITION REPORTING PRACTICES

Basic road condition reporting systems that exist today are composed of four functional components that represent stages in the transfer of road condition information from field observations to visual or aural representations received by road condition report users. The stages include:

1. Field observations of road conditions;
2. Entry and/or submission of road condition observation summaries;
3. Collection of road condition observations at a central site; and,
4. Composition and dissemination of road condition reports.

The primary objective of this design is and has been historically to transform road and weather condition observations made by representatives of the government into reports that provide road condition reports to highway users and other agencies responsible for safety and mobility within the transportation network. For sake of clarity in this document, the description of road conditions created by personnel in the field shall be called observations, and the information disseminated by the state to subsequent users shall be known as reports.

The architecture of existing road condition solutions is shown diagrammatically in Figure 1. From a physical perspective, the four functional stages occur in three separate domains:

- Field locations;
- One or more centralized data or information processing centers typically collocated with DOT and/or SHP headquarters; and,
- The end user’s location.

In Figure 1, the field observation stage takes place completely in the field/remote domain. Once this information is observed it is consolidated and transferred to a central processing location. This process represents a bridge or nexus between the field domain and the central site. The collection and consolidation of road condition observations takes place at the central processing center. Finally, during the fourth stage, the road condition information is synthesized for end user consumption at the central processing center and then disseminated to interested road condition information users. The specifics of the four stages are covered in the remainder of this section.

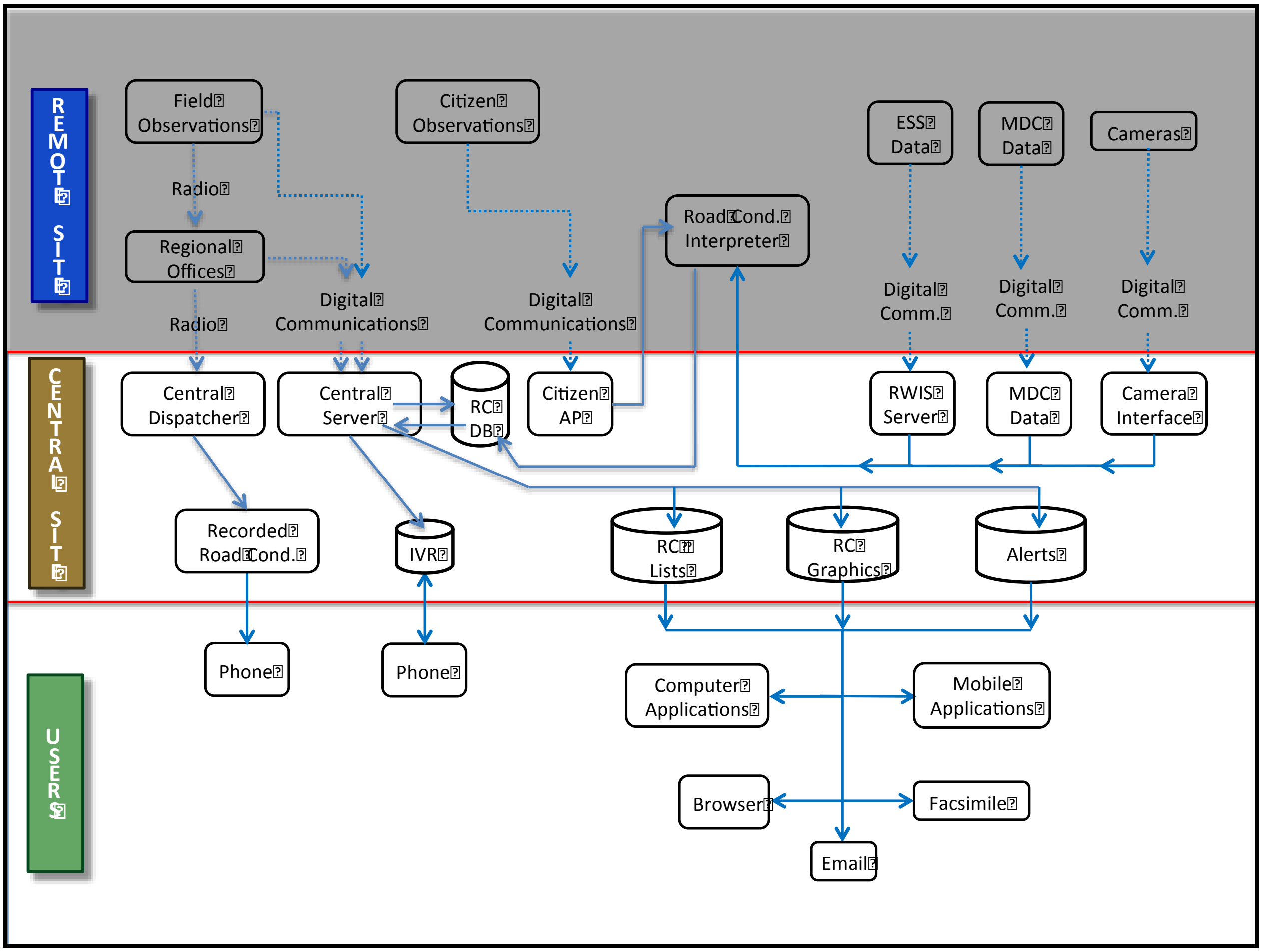

Figure 1. The architecture of existing road condition reporting systems and the data transfer within the systems

2.1 Field Observations

The field observation of road conditions is mostly done by direct observation of road conditions during the performance of normal working responsibilities. Different states assign this obligation to specific agencies and/or groups within an agency. Two of the eight North/West Passage states designate the SHP as the responsible agency, while the remaining states assign the duty to members of the DOT. For those states where the DOT has principal responsibility the observations are done mainly by field personnel, especially by snowplow drivers and individuals responsible for active maintenance of the highways in inclement weather conditions. This pool of field observers is augmented in some states by field supervisors routinely traveling the highway network within their jurisdiction or by highway patrol officers exchanging information with the DOT maintenance personnel via radio. At least one state permits their District engineers and staff from the state office to report conditions when they are mobile. Finally, one state has found that it benefits from the integration of observations from trusted, non-DOT sources. The participants in this program are citizens routinely traveling remote highway stretches the DOT frequents less often than heavily traveled urban highways. Part of the determination regarding who performs the field assessment depends upon what mechanism the state has established and uses to collect, enter, and/or submit the observations. This will be discussed further in Section 2.2.

Over the last 20 years, two additional intelligent transportation system (ITS) technologies have proliferated and provide a supplemental source of information to support the road condition reporting system. Camera imagery was initially integrated into traffic operations to monitor traffic flow, incidents, and congestion; however, maintenance personnel quickly realized the value of this camera imagery to provide a remote eye on weather and road conditions. The integration of camera technology into maintenance operations occurred rapidly as the initial limitations of image acquisition and display were resolved. The following factors were pivotal to the acceptance of cameras as a resource:

- Improvement in image quality
- The introduction of pan, tilt, zoom capabilities to meet transportation requirements
- The introduction of infrared techniques for nighttime use
- Improvement in image compression techniques
- Significant reductions in communications costs associated with new wireless communication techniques
- Substantial reductions in the cost of equipment
- The value of right-of-way imagery for multiple government agencies having differing responsibilities
- The value of highway-related imagery for the traveling public
- The installation of cameras within snowplow cabins to view the roadway

As these technological advancements evolved camera imagery became an important resource for maintenance personnel and has recently been integrated into road condition reporting activities.

Road Weather Information Systems (RWIS) are the second supplemental source of information available to support road condition assessments. RWIS in this discussion is construed to encompass those systems that collect weather and pavement information from the highway environment via monitoring devices and transmit the collected data electronically to a central processing location for subsequent dissemination to users. The initial phase of RWIS was the development of stationary data collection platforms called Environmental Sensor Stations (ESS), which were almost universally located in the highway right-of-way and were designed to collect weather and road conditions at or near the ESS. From the 1970s until the early 2000s, sensors implanted in highway or bridge deck pavements provided road conditions (pavement temperature, status of the road condition, freeze point temperature, and concentration of chemical). Shortly after 2000, remote sensing devices using infrared techniques were introduced. These devices provided pavement temperature; relative amounts of snow, ice, and water; status of the road condition; and, an estimate of the friction level. The second phase of RWIS was the development of mobile platforms to monitor road and weather conditions.

Mobile platforms were recognized as Mobile Data Collection (MDC) systems and required Automated Vehicle Location (AVL) technology to provide the proper characterization of observations from specific locations and time in a dynamic mobile data collection process. MDC/AVL builds from the previously existing spreader controller technology, which has evolved as a separate capability, to provide in almost real-time the output treatment application information from the spreader controller. The data set from MDC/AVL units differs somewhat from the ESS devices. Parameters measured directly by MDC/AVL systems include pavement temperature, pavement condition, air temperature, relative humidity, spreader rates, plow position, and a number of vehicle bus parameters. All data are transmitted with the date, time, and GPS location at the time of the observation. Several of the MDC/AVL solutions also integrate touch screen technology that permits vehicle operators to input observed weather and pavement conditions, material spread rates, and which lane is being treated.

Both the camera imagery and the RWIS data are transported via digital communications through communication networks that are totally separate from the primary road condition reporting networks. In most cases the individual who evaluates road conditions from the camera and/or RWIS data is not the same person providing the field observation.

2.2 Entry and Submission of Road Condition Observations

The method described in the Introduction was used for years to collect and consolidate road condition observations. Observations were prepared by personnel in the field and communicated to one or more points of contact via radio communications, typically regional dispatchers within the DOT or SHP. The verbal assessment of conditions on specific routes or road segments were captured by dispatchers and written down along with the time. To perform the transfer of information as accurately and efficiently as possible, states developed dictionaries of permissible terms and simple codes to minimize the communication time. At specific intervals or as the need arose the summary of observations collected by the regional dispatchers were transferred to the central dispatcher within the state, which became the central repository for all road condition observations. For many states, this data communication architecture for road condition observations remains intact. Over the last ten years, mobile phones, laptop computers, and even tablets have been integrated into the system as a communication resource.

The transfer of road condition observations from the field observer to regional or local dispatchers has traditionally occurred through radio communications. However, the introduction of computers offered a way to make the logging and subsequent transfer of observation sets to the central processing site more efficient. Simple data logging software applications were developed by most states to eliminate the hand-written logs, and procedures were established to transfer the electronic copies to central dispatch. Improvements in the functionality of statewide data sharing networks and the rapid expansion of the Internet allowed states to develop or procure road condition reporting systems. These systems allow entry or road condition observations by dispatchers as they receive the information from the field via radio communications or phone. States are investigating methods to allow direct entry of observations from the vehicle but a suitable solution has not been implemented. The regional dispatcher may enter the observations as aggregates, or send individual observations immediately as he/she receives the verbal observation and enters it via the interface.

2.3 Centralized Collection of Road Condition Observations

The central processing center is the hub of the entire road condition reporting system. In the past, this was usually the central dispatch center for the SHP or a division of the DOT. As the data collection process was computerized the actual data communications and processing has migrated to the Information Technology (IT) group, although oversight for the program remains with the SHP and/or Maintenance division of the DOT. The collection and storage of all road condition observations at a single site offers the following benefits for the statewide programs in the various states:

- Consistency in the content and terminology
- A single site for storage and archival of road condition observations
- A site for colocation of the storage and archival of road condition reports
- A management tool to assess the level involvement of all divisions/units in the road condition reporting program
- A resource for subsequent rapid generation and dissemination of road condition reports

2.4 Composition and Dissemination of Road Condition Reports

The central processing centers for the state road condition systems in the eight states were established to collect road condition information from multiple sources, consolidate the information into logical data sets, and make the road condition information available to a variety of users. The original design revolved around radio communications as the input source and phone or broadcast as the output. Central dispatch acquired the observations from throughout the state and recorded routine updates for delivery via the phone to the public or media. The fundamental architecture of this system has remained intact; however, the entire data processing schema has been replaced by computer-based solutions. The input of digitally based data permits expedient transformation of road condition observations into discrete data elements in a logical database structure. From there software can extract data and compose it into text listings, map displays, or messages that can be voice synthesized.

Today, road condition information can be disseminated to users via computer applications, web browsers, smart phone applications, the media, telephones, and facsimile transmissions. The user community includes travelers, the trucking community, maintenance operations, traffic management centers, emergency services, schools, the media, social media, weather service providers, and various other interested parties. The dominant outlet has become the state 511 programs, which provide voice synthesized phone messages, alert messaging, and text and graphical road condition information via web browser interfaces and smart phone applications. The majority of the 511 guidance occurs via phone, but the 511 program web interfaces have become the de facto standard for communication of road condition information via the Internet. Most state 511 web interfaces integrate the simple graphics-based point and click technology to permit easy access to site-specific information of interest to the user. All of the 511 phone solutions provide voice recognition techniques and/or touch-tone request entry for interaction with the user and all provide voice-synthesized or recorded voice response of the specific information requested by the user. Most 511 systems permit users to set up exception criteria for conditions on routes of interest. When these conditions exist the 511 systems will initiate notification messages that may be sent to an email address, a smart phone application, as a text message, or display as an alert notification on the user’s web browser or phone application.

2.5 Characterization of Visual Observation Techniques

Understanding how an observer assesses certain road conditions is important in that these visual techniques serve as the benchmark for road condition assessment and any automation process must be capable of producing an equivalent ability to define the road condition. Road condition reports primarily address the driving conditions on the surface of highways. However, weather conditions included in road condition reports do provide some guidance on the prevailing state of the weather and its potential influence on these road surface conditions. Occasionally, road condition reports include information regarding other obstructions to driving conditions (rocks, avalanches, animals, etc.) and traffic-related activities, but the primary intent is an indication of the weather's level of impact on road surface conditions and visibility.

Techniques to automate the road condition reporting process will require methodologies to observe or infer the factors in Table 1. These techniques represent what may be considered existing best practices. Visual assessments of road conditions are based on the state of the road surface and the physical influence these road conditions have on the character of the visual image that reaches the observer's eyes. The discussion describes the characteristics of each of the parameters listed in Table 1.

Table 1. Parameters observed and reported in typical road condition reports

Road Surface Conditions	Visibility/Weather
Dry	Dust
Wet	Smoke
Snow	Fog
Slush	Snow
Packed snow	Blowing snow
Drifting snow	Freezing rain
Frost	
Ice	
Sleet / Hail	

2.5.1 Dry

Visual assessment of dry pavement is to some extent based upon the physical appearance of a dry pavement surface; specific visual characteristics include:

1. the hue of the particular pavement material;
2. the degree of light reflection; and,
3. the observer's ability to discriminate surface characteristics such as roughness, grooving, cracks, patches, and surface irregularities.

Dry pavement surfaces tend to have isotropic luminance such that the apparent surface brightness of a given location on the pavement surface is the same regardless of the observer's angle and direction of view. Light rays hitting a pavement surface reflect off the rough surface in all upward directions nearly equally creating a uniform appearance from any viewing position.

Although the three factors indicated may compose part of the mental decision logic in the determination of dry conditions, it is more likely that the assessment of dry pavement conditions is based on the exclusion of the visual characteristics of all other potential road condition categories.

2.5.2 Wet/damp

Wet or damp road surfaces appear darker than dry pavements. The primary cause of this decrease in the luminance of wet pavement surfaces is associated with two features of water films, which are illustrated in Figure 2. First, water films cause a specular (mirror-like) reflection of part of the light. Second, rays of light energy that enter the water are bent slightly, reflect off the pavement, and return to the water-air interface. At this surface, part of the light is reflected back into the water film and part is passed out into the air. The reduction of the amount of light energy coming out of the water film coupled with some absorption of the light energy by the water reduces the luminance of the surface from its appearance in a dry state.

The glare or sheen noticeable on wet surfaces results from the specular reflection of light from the top surface of the water film. This feature is particularly evident at night when point light sources (e.g., head lights, street lights, commercial lighting) become the dominant sources of light energy. Since the reflective glare is distinctly different from the visual appearance of dry surfaces, this factor becomes a key determinant of wet or damp surfaces. As vehicle tires move through the water film and displace the water, the liquid film is both temporarily reduced in thickness and its laminar surface is disrupted. The modified tire track zone reduces the specular nature of the water film and permits observers to see the difference between the tire track and the surrounding undisturbed liquid film. This tire track pattern becomes another key in assessing non-dry conditions when the surface film is liquid; further, the tire track impressions permit the observer to discriminate the relative depth of the liquid layer.

Traffic also creates spray and splatter patterns that are not only visually distinctive because of the optical effects of the laterally displaced water and/or suspended water droplets, but also due to the visual obstruction they induce on a vehicle’s windshield. The type of spray/splatter pattern varies based on the depth of the layer, the vehicle speeds, and the vehicle type. Drivers develop the ability to correlate the general depth of water on the road associated with specific spray and splatter patterns and they refine the depth classification with observations of the appearance of the pavement surface condition. From these observations drivers can characterize water depth categories such as moist, damp, wet, flooded ruts, potential hydroplaning conditions, and flooded.

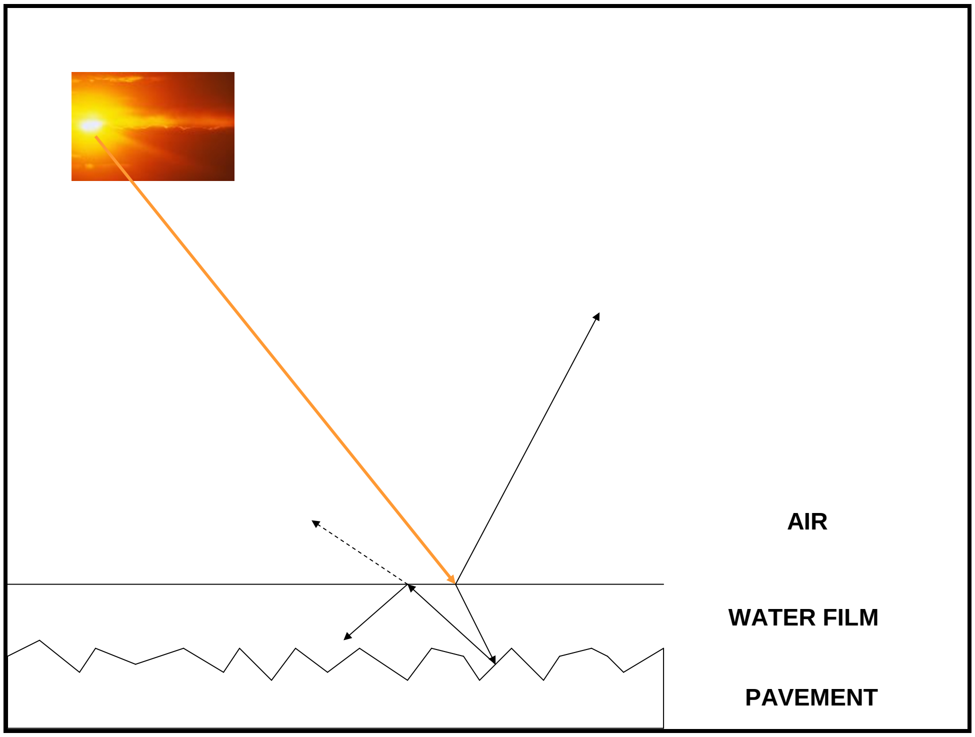

Figure 2. Diagram of specular reflection of a water surface and the reflection-refraction interactions within a water film

2.5.3 Snow

Falling snow has a distinct white hue that is caused by its high level of reflectivity within the visible light spectrum. Since snow occurs as ice crystals or snowflakes, which have a predominantly flat planar structure, it has a significantly lower terminal velocity than other forms of precipitation. These two features give snowfall a distinctive character that is easily discernable from rain, sleet, hail, and ice pellets. The delicate crystalline structure of the falling snowflakes may be partially shattered as the they reach the pavement, but the snowflakes or their resulting fragments remain as discrete structures where they come to rest.

When it is undisturbed, freshly fallen snow has a granular appearance because it is an accumulation of individual snowflakes and ice crystals. As snow starts to accumulate on pavement surfaces but is insufficient to totally cover a road surface, turbulence associated with the wind flow across the roadway or passing traffic creates visible wisps or streamers of snow. Once the snow totally covers the roadway and the individual snowflakes start to bond to one another, horizontal movement is reduced and visually the snow forms a relatively uniform layer that obstructs visual observation of the road surface. Although the top surface of fresh snow appears uniform and roughly parallel to the underlying surface from a distance, the surface itself, from a microscale perspective, is irregular and composed of an array of ice crystals having random orientation.

Fresh snow surfaces reflect nearly all visible light. For example, dry snow typically has an albedo of 0.8 – 0.95 and wet snow surfaces are more likely in the 0.7 to 0.9 range. Because the albedo of fresh snow is so high, the random orientation of the surface ice crystals cause the surface to appear nearly isotropic, but with occasional sparkles caused by mirror-like reflections from the flat surfaces of snow crystals.

Undisturbed fresh snow is composed of ice crystals and air; thus, it has a density that is less than 10% that of water. Typical densities range from 50 – 100 kg/m^3 (3 – 6 lb/ft^3). Snows that occur near 0°C (32°F) tend to be wet and 'heavy' and have a density in the 100 – 200 kg/m^3 (6 – 12 lb/ft$^{3)}$ range. Since a large portion of a given volume of fresh snow is air, its compressive strength is less than 7 kPa (1 psi), which allows easy compaction of a layer of snow. These physical characteristics of snow are important because they provide an understanding of what happens to the snow layer on the pavement surface when it is exposed to traffic and subsequently what an observer sees. This is discussed further in the section on Packed Snow.

2.5.4 Slush

Any deicing material in a layer of snow will cause a portion of the snow to melt at a temperature below 0°C (32°F) creating a layer of snow, an aqueous solution containing the dissolved portion of the chemical, and any remaining solid form of the chemical. For a given amount of applied and/or residual chemical the percentage of the layer that is composed of ice crystals and the portion that is liquid depends upon the temperature of the layer. Even when salt is used some of the layer will still contain a liquid component down to - 21°C (-6°F). Water generally has an albedo in the range of 0.1 – 0.2, although it varies somewhat depending upon the incident angle of the visible light source. Because the albedo of water is so much lower than pure snow, the amount of light that is reflected from slush is less than from snow and slush appears darker than snow. This becomes particularly noticeable as the water content increases; wet slush becomes darker with increased water content, and even appears to be dirty snow.

Traffic impacts the appearance of slush by redistributing the position of the snow, ice, and liquid components of the slush layer. When the composition of the layer is predominantly snow, the impact of traffic is mostly compaction with some scattering of compacted snow debris ejected from tire treads or due to rolling friction of the tires. As the percentage of water increases in the slush layer, horizontal mixing increases due to lateral splattering of the liquid-ice mixture. The sharp delineation between the undisturbed snow layer and wheel tracks gives way to an irregular surface that has a mottled to sloppy appearance depending upon the percentage of the liquid component and the traffic volume. The transition from predominantly snow layers to wet slush layers occurs gradually as the percentage of the liquid component increases from zero to 80 to 90% and the visual characteristics of the slush layer and how it reacts to traffic permits an observer to make a reasonable estimate of the percentage of ice and water in the slush.

2.5.5 Packed snow

Vehicles driving across fresh snow compact the snow by compressing the snow layer and forcing the air out of the layer increasing the density of the resulting snow layer. The instantaneous pressure of tires compressing snow beneath the tire also causes the temperature of the snow to rise instantaneously on compression and return to its ambient temperature upon decompression. The temperature rise is sufficient to melt some of the ice crystals, which refreeze once the tire has passed. The amorphous ice that forms has a higher denser than the crystalline portion of the layer, thus this refreeze process adds to the density of the compacted layer. Snow with an initial density of 50 – 100 kg/m^3 (3 – 6 lb/ft^3) will increase to a density 400 – 500 kg/m^3 (25 – 30 lb/ft^3) under repeated vehicle traffic. If hard pack remains on a roadway surface and is continually impacted by traffic the density will continue to increase and may reach densities around 775 kg/m^3 (50 lb/ft^3).

The albedo of the compacted snow typically falls in the 0.4 – 0.5 range, thus the compacted snow in the wheel tracks reflects considerably less light and appears darker than the fresh snow surface. A snow layer on a roadway surface then is characterized as a highly reflective snow surface with distinct tire-induced tracks that are depressed from the snow surface and that appear darker than the surrounding snow. As these wheel tracks are compacted further and their density approaches that of ice, the wheel tracks take on a sheen due to the specular reflection of the ice surface. This is especially true where traffic counts are higher and the top surface of the hard pack continually goes through a refreeze process, which forms a thin layer of amorphous ice on the top surface of the hard pack.

2.5.6 Drifting snow

From the visual perspective, drifting snow has the same or similar appearance as snow. What differentiates drifting snow from snow is the smooth variation in the depth of the snow either along or across the highway. Since variations of depth may be caused by other factors (e.g., plowing and traffic), the assessment of drifting based on a static view of the drift typically requires an assessment of continuity of the drift from the shoulder of the road or further from the roadway surface. The assessment is based upon a specific shape associated with the drifting process. More often, drifting is determined by the active movement of snow onto or across the roadway as an ongoing process. This requires a sequence of observations and recognition of a horizontally induced change in the depth of the snow. Clues to the movement of snow typically come from observed conditions adjacent to the roadway surface in the fetch or source area for the drifting snow or from the recognition that wind speeds are adequate to cause saltation and movement of snowflakes onto or across the highway.

2.5.7 Frost

Frost is the deposition of ice crystals on the highway surface. Deposition in this case is a physical change in the state of water from its vapor state to its solid state. When the pavement temperature is below freezing and below the dew point temperature, the pavement is able to extract enough heat from the water vapor molecules to cause them to form ice crystals and adhere to the surface of the pavement. The ice crystals that form are very small, but as the number of ice crystals increases the nearly microscopic crystals form a layer of granular ice on the surface of the pavement. The hexagonal structure of ice crystals causes them to be translucent so light striking the layer of crystals enters the ice crystals and all wavelengths of light are refracted back from internal crystalline surfaces equally giving frost a white appearance. When light strikes a crystal surface and is reflected back, the eye sees a brief bright reflection or sparkle from the crystalline surface.

Frost is particularly apparent on a roadway surface in locations where the frost has not been disturbed. Since the crystalline structure of frost is very fragile, traffic quickly disrupts new frost accumulations and makes frost more difficult to discern in wheel tracks. Thus, the presence of frost is typically noted from the presence of a white layer on sections of the roadway that have not been traveled. Since frost does not appear significantly visually different than undisturbed snow, the classification of frost really requires knowledge of the absence of precipitation as a source of the white layer on the roadway surface.

2.5.8 Ice

Ice is an amorphous form of frozen water that exhibits no crystalline structure. It forms from the direct change of water to ice. On roadway surfaces this transition may occur in the following ways:

- A film of water with no dissolved chemical that freezes as the temperature of the pavement drops below 0°C (32°F)
- A film of water with dissolved chemical that drops sufficiently below the freeze point temperature of the solution to permit the layer composition to contain more than 80 85% ice
- Rainfall that falls on pavements below 0°C (32°F)
- Super-cooled raindrops that strike pavements at or slightly above 0°C (32°F)
- The refreeze of ice crystals (snow or frost) that have been compressed by tire traffic

Ice has a density of around 900 kg/m^3 (58 lb/ft^3). Its rigid structure is due to the covalent bonding of the hydrogen molecules in the H_2O structure of ice. This covalent bonding also binds ice to other structures, such as the asperities in the texture of pavement surfaces making ice relatively difficult to remove through mechanical means such as plowing.

Ice is generally transparent and difficult to recognize on a pavement. Ice absorbs less light than water and therefore takes on a lighter hue and one close to that of the surface beneath the ice layer. Since ice tends to absorb the red wavelengths it may take on a bluish color when the layer is thicker. The top surface of a layer of ice is highly reflective and gives ice surfaces a sheen. This specular reflection of light by ice creates discrete bright spots on the ice surface as light from brighter sources is reflected to the viewer’s eye. However, the specular reflection of ice is not significantly different from that of water films, and it is difficult to visually discern ice surfaces from water surfaces.

Ice has a coefficient of friction that is around 0.3 or lower. This is lower than essentially all other materials that can impact the friction of the pavement surface. Because ice is difficult to detect visually, drivers often fail to recognize the potential to encounter this low coefficient of friction and are not prepared to deal with its impact on the driving conditions.

2.5.9 Sleet/Hail

This classification group actually contains three distinct types of precipitation that fall as different forms of ice. Sleet is defined as ice pellets in the United States, and a mixture of snow and ice in Canada and Europe. In this discussion, sleet is considered as small spherical forms of ice. Ice pellets form when snow aloft falls through a warmer layer, turns into water droplets, and then fall through a sub-freezing layer to form into pellets. Graupel forms when falling super-cooled water droplets overtake a snowflake and form a rime around the snowflake. Unlike the dense, hard structure of ice pellets and hail, graupel tends to be fragile and will easily crush into fragments when touched. Hail forms in turbulent convective environments where water droplets are forced to rise vertically into colder air where they freeze. These frozen droplets are then repeatedly thrust upward accreting additional layers of ice. The individual ice forms may bump into other balls of ice forming larger irregular chunks of ice or hail stones.

When these forms of precipitation reach the roadway surface they form a layer of discrete ice objects. Normally, these are mostly spherical in nature, but with hail they may take on a structure more akin to rock gravel layers. The individual components appear off white in hue because of their spherical structure and their development in a riming manner. Visually, the individual objects are observable and give the layer a granular or marbled appearance that is distinct from snow. If the sleet or hail is accompanied by rain the appearance will be modified to appear more as a slush with the effects of the liquid layer interacting with the sleet/hail character. Often these types of precipitation fall on pavements that are above freezing so the distinct character of the ice pellets, graupel, and hail quickly transition into the visual appearance of slush and then wet layers.

2.5.10 Dust

Dust in the air is recognized by its impact on visibility and the color of material that is causing the visibility reduction. Dust in a particular location tends to have a brownish or blackish hue associated with the soils in the area, but the hue may exhibit the dominant color of the local soils or a particular source of particulate material, such as an industrial plant that creates dust as part of its manufacturing process. A predominance of dust in the air requires a force to keep the dust suspended. The typical source is sustained winds, thus the recognition of dust conditions often includes the observation of relatively windy conditions.

2.5.11 Smoke

Smoke is a collection of airborne solid and liquid particulates as well as gases generated when materials undergo combustion mixed together with the surrounding air. The size of the particulate matter affects the visibility and characteristics of the layer of smoke. The type of particulate matter derived from the source of combustion influences the visibility and the hue of the cloud created by the combustion. Therefore, smoke clouds may range from nearly invisible to a near complete extinction of visibility, and the color of the smoke cloud can very from white to black through all shades of gray. Occasionally, smoke clouds will take on a slight coloration due to a preponderance of a unique combustible material.

Observation of smoke is dependent upon recognizing the obstruction in visibility, either as it impacts the sight range at the observer’s current position or can be seen as visible cloud between the observer and the horizon. When smoke is present locally, smell becomes a secondary clue that the obscuration in visibility is smoke-related.

2.5.12 Fog

Suspended water droplets cause fog when the difference between the air temperature and the dew point temperature is small (typically less than 2.5°C (4°F). However, most fogs occur when the air and dew point temperatures are equal and the relative humidity is 100%. Fog tends to occur when there is little or no wind since this allows the water droplets to remain suspended and avoid collisions with other droplets, which yields larger droplets whose weight may cause them to fall out of the suspension. Water droplets absorb and scatter light rays, thus as the density of suspended droplets increases the visibility decreases., The appearance of a fog layer is determined by the amount of light that gets through to the observer because the water droplets absorb light energy. As fog gets denser, it appears darker due to reduction in transmitted light.

The conditions conducive for fog development are often driven by local topography. Areas that cool more quickly than surrounding areas or where cooler air pools may decrease the air temperature in that locale to the dew point temperature and force the development of fog in valleys or low lying areas. Fogs can also develop over areas where residual snow remains during the spring snow melt. Fog also occurs in areas where there is an open source of water and the more humid air from this body of water gets carried over cooler surfaces in the surrounding area.

In these type of local situations fog is recognized by its visual presence within the broader, unaffected environment. When weather conditions permit an expansive outbreak of fog, fog is recognized by its reduction in visibility reduction. Since fog has the many of the characteristics of smoke in appearance, a firm determination may require knowledge that combustion was not a probable cause and the lack of odor associated with smoke.

2.5.13 Snow

The observation of falling snow requires the ability to see changes in downward movement of snowflakes over a period of time. Because of the reflective characteristics of snowflakes and ice crystals and their slow terminal velocity compared to other hydrometeors, observers can recognize the presence of snow relatively easy, especially when the snow is viewed against a dark background. Observers can sense the presence of snow without actually seeing the movement of individual snowflakes by the reduction in visibility that snow causes. Visual observations at night require a reasonably bright source of light. The reflection off the snowflakes and their vertical movement of the flakes in time steps on the order of tenths of a second provide the visual clues to verify snow.

2.5.14 Blowing snow

The observation of blowing snow follows techniques similar to those used for assessment of snow, except in this case the motion of the snow must be predominantly horizontal. In reality, the determination of blowing snow requires the determination in most situations that falling snow is not present. The bigger challenge with blowing snow is that it can vary with distance along a highway segment and a true determination of blowing snow may require the presence of snow moving horizontally at one or a small number of locations along a segment where no blowing snow exists at other locations.

2.5.15 Freezing Rain

The observation of freezing rain is formidable, as it requires a visual assessment of rain. Visually, rain can be partially determined by vertical streaks of raindrops in sequential snapshots of the same volume of air against a dark backdrop. However, assessing the presence of rainfall in a given volume of air is sometimes difficult to do unless there is adequate lighting. Often it is easier to see the effects of raindrop collisions with the windshield of a vehicle or the glass in the window of a building. An observer can see water appear on the glass as the drops hit the glass surface. There may be the appearance of a drop of water on the glass where none existed previously, a splatter of the water drop as it impacts the glass, or the development of liquid streaks as the weight of the water causes it to run down the glass.

An alternative approach is to monitor the state of a horizontal surface of pavement over time. The surface state parameters one needs to monitor depend on the initial state of the surface. If the pavement is dry, it is possible to see the start of a rainfall event by the change in the hue of the surface as it transitions from dry to wet or damp. If the pavement is already wet or damp, then one must watch for indications of rain disrupting the film of water on the surface. The best method to visually assess the impact of falling rain on the surface is to place a light source opposite of the observer's viewing position and watch the changes in the reflection pattern of the surface over time.

Those techniques provide a good indication of rain; the big challenge is the determination of freezing rain. Visually it is difficult to see the difference between a wet surface and an ice-covered surface. The reflection/refraction patterns are very similar. When the ice layer reaches a depth of around 2 mm (0.1 in) it becomes easier to see both the underlying surface and the surface plane of the ice layer; however, this assessment requires a high level of scrutiny. The best supplementary technique to determine that the precipitation is forming ice is to determine whether the surface friction is less than what would be expected for a wet layer of pavement.

The assessment of freezing rain must integrate several different observations in order to make the correct determination that a rain event is actually a freezing rain event.

2.6. Existing Best Practices for Road Condition Reporting

The existing schema for reporting road conditions to users of the highway infrastructure includes collection of road condition information from the field, consolidation and processing of the field information, and dissemination of the information for user consumption. All states have implemented this fundamental design and evolved the schema as their own unique solution over many years. Figure 1 encapsulates the basic components of the schema and shows the variety of techniques that states use. The original design of this road condition reporting architecture revolved around sole use of radio communications for collection and dissemination of road conditions and manual transfer from input to output. This is shown diagrammatically on the left side of the figure. The design utilized visual observation of road conditions by government employees who were actively traversing the roadways in the highway infrastructure. This fundamental approach remains the foundation of current road condition reporting solutions.

In current best practices digital communications, supported by computer applications, has replaced the radio communications and the computer-based solutions have replaced the manual transcription of road condition input to output formats. A network of computer applications handles the end-to-end transfer of field observations all the way to the user interface points shown at the bottom of Figure 1. Government employee involvement is limited to entry of digital representations of the road condition observations (typically at a regional office) and possible control of the release of road condition reports at the central location prior to the automated dissemination of the road condition reporting products. With the expanded use of smart phones, tablets, and in-vehicle computers some agencies are testing direct entry of road condition observations by field personnel, which would completely replace the previous radio communication solution.

States have modified this fundamental paradigm as particular unmet needs surfaced or new capabilities arose. All of the modifications result from the realization that there are resources other than government personnel that monitor and report field conditions and could augment the basic road condition monitoring system. One resource is citizens that spend a considerable amount of time traveling the state's highway systems to use programs permitting interested citizens to submit their road condition observations via secure web interfaces provide a mechanism to increase not only the coverage but update frequency of the road condition reports. These programs do require oversight and, depending upon State policies, citizen observations may require approval at the central processing center before integration into reporting system. The other source of field reports come from data collected from RWIS sites, cameras, and MDC mobile platforms. Each of these resources have their own unique data collection and processing networks that consolidate the data from their respective field sources at a central database associated with that system or data type. Since these databases are state-owned resources, the information is readily available to support the road condition reporting requirement. However, the data from all three of these sources must be interpreted and converted into acceptable road condition classifications. This must be done by an individual or individuals who are familiar with the data or images and who know how to interpret and transpose the resource information into valid road report classifications. This function is illustrated in Figure 1 by the inclusion of a Road Condition Interpreter between the non-government employee sources and the Road Condition database. The box in the diagram is shown as a field-related function; however, performance of this function may just as well be done at the central site or may be accomplished by different individuals both at headquarters and at remote locations. The important point though is that all of these sources need interpretation before going into the road condition report stream.

Logistically the best practices scenario defined above reflects the current state of the art. However, from an external perspective, there are two modifications that end users would find desirable. First, it would be advantageous to have consistency in road condition nomenclature across jurisdictional boundaries based upon a well-defined, published set of road condition criteria. The road condition classes should be supported by good descriptions and associated image characterizations. Second, there is a need for the uniform inclusion of the date and time associated with each road condition observation. Some states do provide the time stamp with the observation, but this feature should be available from all agencies. The inclusion of a time stamp is a necessary resource for proper use of the road reports delivered to the end user; however, a more effective presentation may be the age of the report from the current time. Since most road condition display pages currently available to the end user are a response to a query, they remain static in time. Therefore, the current time that the page was generated needs to be included along with the age of the road condition report to make the report age an effective tool. Also, where agencies provide updates at routine intervals, it would be helpful to have guidance regarding when the next update is expected.

3. MOBILE SENSORS

Sensors exist to monitor an ever-expanding list of parameters and/or operational states both within the vehicle infrastructure and in the environment in which the vehicle is traveling. The automobile industry developed internal communications network (or vehicle bus) during the last quarter of the Twentieth Century that interconnected vehicle components for more effective vehicle operation and performance diagnostics. During the same time period technologies that supported global positioning system (GPS) technics matured and became available to monitor the location of mobile assets. These automated vehicle location systems reached the market and gradually were added to vehicle inventory to support fleet management requirements. Manufacturers of snowplows and material spreading devices and controls developed electronics-based spreader controllers, which then replaced the mechanical linkages previously used. The controllers not only managed the various equipment used to spread the desired materials at the appropriate rates but also logged the settings for subsequent use in assessment of material utilization. As the spreader controller technology matured, manufacturers integrated GPS and added other monitoring capabilities such as plow position, light status, and numerous vehicle bus parameters pertinent to maintenance activities. The controller integrated these parameters into the logs.

By the mid-1980s, the RWIS program had demonstrated the value of knowledge of pavement temperature in winter maintenance activities and sensors using infrared technology were developed for installation on maintenance vehicles to permit continuous monitoring of the roadway temperature. The sensing capability was expanded to include air temperature to the outside mounted device and a simple display was placed in the vehicle cab so drivers could monitor these conditions. In some cases the output of these sensors was integrated into the spreader controller logs.

Prior to 2000, the data collected the spreader controllers were retained on the controller until the vehicle returned to a maintenance facility where the logged data was transferred to other data processing applications. However, there was a desire to have routine access to the information from the vehicles to support maintenance management activities. Two things happened in the period shortly after 2000. First, telecommunications capabilities reached the point where the transport of digital data from a mobile vehicle to a central site became an economical reality. Much of this was driven by cellular technology. The second factor was the development of the MDSS program and the need for mobile data to support the real time knowledge of road conditions and material applications. The data requirement for MDSS led to the development of MDC controllers that routinely collected and communicated maintenance information that was necessary to support MDSS and of value to the supervision of ongoing maintenance operations. The key data components were vehicle location, the type and rate of material application, and pavement conditions (road state and pavement temperature); but, MDC became the conduit for additional information such as plow status, weather conditions, camera imagery, and the operational state of vehicle systems. The MDC controllers incorporated two separate input interfaces: automated transfer of readings from mobile sensors and driver input of observed or known conditions via a touch pad interface. This operational characteristic of MDC controller solutions becomes an important consideration in the automation process and the subsequent determination of the degree of automation that may be utilized in road condition reporting.

The remainder of this section addresses each of the sensors that are currently used on MDC systems or that are being tested and/or in the early stages of integration into these systems.

3.1. Atmospheric sensors

Weather information is an important part of the information that is transferred via MDC; however, only air temperature and relative humidity are routinely acquired directly from vehicle-mounted sensors. Vehicle operators provide the remaining parameters through the use of a touch screen interface. These include type of weather, type of precipitation, precipitation rate, snow depth, and visibility.

3.1.1 Air temperature

The air temperature sensor may be any temperature sensor present on the vehicle; however, to meet RWIS standards the temperature sensors have typically been limited to sensors that have been marketed specifically for road weather use. The primary sources to date have been the Surface Patrol and Road Watch sensors, whose specifications are shown in Appendices A.1 and A.2 respectively. The sensor specifications indicate a temperature accuracy of ± 1°C in the range of -40°C to 50°C (-40°F to 122°F). Air temperature sensors tend to work indefinitely without maintenance; however, the observed temperature readings should be compared to a known standard at least once a year.

3.1.2 Relative humidity and dew point temperature

For maintenance purposes the dew point temperature along with the pavement temperature provides an important indicator for the potential of frost and dew formation. The dew point temperature is not measured directly but is derived from measurement of the air temperature and relative humidity. The Surface Patrol sensor in Appendix A.1 is a good example of a relative humidity/dew point temperature sensor. The humidity-sensing component of the sensor uses a capacitance technology to sense the level of humidity in the air passing the sensor. The accuracy range of the capacitive measuring device is dependent upon both the temperature and the humidity of the air. Fortunately, the highest level of accuracy is achieved at humidities above 70% and for temperatures around freezing, which are the ranges critical to maintenance concerns. During these conditions, the sensors provide a dew point temperature accuracy of ± 2°C. This level of accuracy becomes a concern in an automation approach since the development of frost is very critical on the relationship between pavement temperature and the dew point temperature and inaccuracies in the dew point temperature have the potential to induce errors in the determination of frost (both an indication of frost when frost conditions do not actually exist or no indication of frost when frost conditions actually exist). Supplemental observations of other parameters will be necessary to improve the decision logic for the presence of frost.

3.2. Road condition

From an RWIS perspective the classification of road condition really contains two separate parameters: pavement temperature and pavement condition status. The RWIS descriptor STATUS is typically what is called road condition when we are talking road condition reports. However, an investigation of automation of road condition reports must address the pavement temperature as well as the status.

3.2.1. Pavement temperature

Pavement temperature is measured using pyrometry, a technique that measures the infrared radiation energy emitted by a surface. The amount of infrared radiation from an object is directly proportional to the temperature of that object. The two non-contact sensors introduced prior to 2000 and installed on numerous maintenance vehicles were the Road Watch sensor developed by Sprague Controls and the Surface Patrol sensor developed by Control Products. Rights to manufacture and distribute both of these sensors have subsequently been acquired by different organizations. Specifications for these two sensors can be found in appendices A.1 and A.2. Apogee Instruments has marketed infrared thermometers for agricultural use. They offer a model with a horizontal aperture (S1-1H1), which is used by a couple of states to monitor pavement temperatures from a mobile platform. After 2000, Vaisala introduced a stationary non-contact sensor, the DST111, and Lufft started marketing the NIRS31 remote infrared sensor and intends to release a mobile version of the NIRS31 in 2013 as model MARWIS. The published accuracy of the mobile pavement temperature sensors is provided in Table 2. It should be noted that Vaisala offers a mobile package that uses their non-contact road condition sensor, DSC111, but use the Surface Patrol DSP101 and not the DST111 sensor.

Table 2. Published accuracy of mobile pavement temperature sensors

SENSOR	MANUFACTURER	ACCURACY (from vendor specifications)
Surface Patrol DSP101	Vaisala	±0.28 °C (0.5 °F)
MARWIS road temperature	Lufft	Est. ±0.8 °C (1.44 °F)
Road Watch	Commercial Vehicle Group	±1 °C (1.8 °F)
Apogee S1-1H1	Apogee Instruments	±0.2 °C (0.4 °F)

Although the measured parameter is specified as the pavement temperature, the sensors actually measure the temperature of the top of the accumulation layer. The accumulation layer is defined as the layer of snow, ice, water, chemical, and/or abrasive that accumulates on a bare pavement surface under different weather scenarios and treatment action plans. In most cases, the temperature of the top surface of the pavement and the temperature of the accumulation layer will be very close to one another and the temperature measured by any one of these non-contact sensors should represent the pavement temperature within the constraints of the accuracy of the sensing device.

A significant consideration associated with calibrating pyrometers is what value to use for the emissivity coefficient in the conversion equation between the amount of energy measured by the pyrometer and the surface temperature that caused this energy output. The relationship between what is called the output energy and the temperature of the object follows this relationship:

$$E = \varepsilon \sigma T^4$$

Where E is the output energy, ε is the emissivity, σ is the Stefan-Boltzman constant, and T is the temperature. If all bodies radiated energy equally ε would be 1; however, ε varies depending upon the material doing the emitting. The variation for typical road surface and accumulation layer materials is shown in Table 3. The object in setting a value for ε in the pyrometer is to select a coefficient that matches the emissivity of most materials for which you want to know the temperature.

Table 3. Emissivity values for typical road and accumulation layer materials

MATERIAL	EMISSIVITY
Water	0.95 – 0.963
Ice, rough	0.985
Ice, smooth	0.966
Snow	0.969 – 0.997
Asphalt	0.93
Portland Cement Concrete	0.85

The documentation for the RoadWatch sensor indicates that the emissivity for the sensor is set to 0.96. Documentation for the other sensors does not include the emissivity values set in those pyrometers, but it is likely that the value chosen is close to 0.96. Since all of the accumulation layer materials have emissivity values close to 0.96, the temperature output by the pyrometers should be representative of the radiated temperature. However, since the emissivity of Portland cement concrete is lower than the configured value the sensor will report temperature values that are slightly warmer than the actual pavement temperature.

3.2.2. Road condition status

Mobile sensors to measure the road condition status have been introduced into the market just in the last couple of years. These mobile sensors use infrared laser technology that has been the resource utilized for stationary, non-contact road condition sensors for the last decade. By using the response of reflected infrared energy in different ranges of the infrared spectrum, the sensors are able to discriminate the depth of water, snow, and ice in the accumulation layer (the layer of snow, ice, water, chemical, and abrasives on a roadway surface). The unique characteristic of non-contact sensors is that they measure the depth of the constituent components of the accumulation layer from the top down, that is they view the top of the layer and not necessarily the conditions at the pavement surface. From this depth information decision logic within the sensor translates the component amounts into one of the generally accepted road condition classes. The sensor logic also provides an estimate of the grip or coefficient of friction based upon the accumulation layer components.

Specifications for the Vaisala DSP310 and Teconer RCM411 mobile road condition sensing packages are provided in appendices A.3 and A.4, respectively. Lufft plans to introduce a MARWIS model mobile sensor suite in early 2013 that incorporates the non-contact pavement condition assessment technology in their NIRS31 stationary sensor. All of these sensors measure the depth of the liquid and ice components in the range from 0 to 2 mm and the depth of snow from 0 to 10 mm. For comparison purposes, damp layers extend from roughly 0.1 to 0.4 mm, wet layers have a depth range from approximately 0.4 mm up to 0.8 mm, and anything above roughly 2 mm is considered standing water. Plowing of ice, snow, and slush typically leaves a layer of 4 to 7 mm (approximately ¼ inch). Thus, it appears that sensors based upon infrared laser technology should be able to measure the accumulation layer components and their depths most of the time during winter scenarios. However, infrared energy is absorbed as it penetrates snow, ice, and water or is reflected at the surface of the layer. Water allows the infrared energy to penetrate the layer and return the IR energy; however, snow and ice trap a larger portion of the infrared energy and it becomes more difficult to measure the depth of snow or ice just by allowing the infrared energy to penetrate the layer. Therefore, depths of snow and ice layers are partially determined by vertical faces like those that would occur in wheel tracks. The infrared sensors perform well when there are thin films (2 mm or less) of snow, ice, water, or slush but have increasing difficulty in representing the correct depths when the accumulation layer thickness gets deeper. Since the aqueous component of mixtures of snow, ice, and water is slightly denser than the snow or ice, it tends to gravitate to the bottom of the accumulation layer. If the layer is not continually mixed by traffic the snow and ice layers will mask the aqueous component such that the sensor cannot pick up the correct depth. The sensors also have difficulty with hard pack, which is an opaque form of ice with a density of 0.5 to 0.7 g/cm^3 (whereas pure ice is closer to 0.9 g/cm^3). This occurs because the compacted snow forms hard pack layers whose depth often exceeds the 2 mm upper limit of the instrument's depth measurement range. Because of the sensors only measure effective depth of the snow, ice, and water components there are limitations on what road condition classes can be reliably reported. The list of road conditions provided by the existing infrared laser sensors includes:

Dry
Damp
Wet
Slush
Snow/Frost
Ice

3.3. Maintenance devices

Snow and ice control activities to mitigate the effects of snow and ice on the roadway may be accomplished in two fundamental ways: physical removal of the snow and ice by plowing or by changing the state of the frozen material to permit easier removal. These activities have significant influence on the road condition at any point during an event even though they are not an explicit factor in the description of the road condition itself. However, systems such as MDSS that offer the ability to infer the state of the road from the integration of a composite of directly measured weather, maintenance activities, and traffic parameters need an accurate input of material application type, material application rate, plow type(s), and plow position. When automation of road condition reporting is viewed from this perspective, the accuracy, reliability, and density of MDC input becomes one of the critical factors of success of the MDSS approach.

3.3.1. Material application rate - solids

Ground speed controllers now almost universally control the automated application of solid treatment materials. Automatic controllers use a truck-speed sensor to adjust the opening of the hydraulic valve that controls the operating speed of the feed mechanism. These speed sensors may be connected to the speedometer-cable, measure the rotation of the drive shaft or a wheel, or use speed from the internal vehicle bus output. There are two types of automatic controllers: open-loop and closed-loop systems. Both types require a truck-speed sensor.

The open-loop system uses the truck speed to adjust a control valve to a predetermined setting to provide the correct belt or auger speed for the desired spread rate. Any changes in the hydraulic system variables will result in an error in the belt or auger speed. The closed-loop system monitors both truck speed and belt or auger speed and adjusts the control valve until a predetermined ratio of belt or auger speed and truck speed is obtained. The potential for a systematic error in delivery rate is greatly reduced by the closed-loop system.

Spreader controls tend to provide accurate representations of the application rate as long as the systems remain calibrated. Normal wear during winter operations can change the calibration of equipment and aging of the equipment causes the spreader's hydraulic functions to impact the operation of the belt, auger, and spinner motors. Also, normal operational issues with materials such as caking or clumping can reduce the actual output below the values reflected by the controller. These situations do occur in normal operations and are typically rectified by the plow operator; however, the automated spreader system is not aware of the material distribution issue and continues to report based upon its configured spread rate. These characteristics may impact the accuracy of the material application data derived from a totally automated process and require some form of manual override when a plow operator recognizes the situation.

3.3.2. Material application rate - liquids

Liquid applications use the same fundamental operating techniques as the spreaders used for dry materials except in this case the hydraulic controls adjust the pump distribution rates for the liquids. When properly calibrated, the application rates associated with the controller setting are consistent; however, gradual aging and wear of the system necessitate routine calibration. Nozzles do clog in the harsh environment at the rear of a plow and need to be checked regularly for proper operation. As with the distribution systems for dry materials, differences between the actual distribution rate and pattern and the measured release of liquid material can cause discrepancies in the application rate provided to MDSS.

3.3.3. Plow position

Currently, there is some metadata on the type of plow configuration present on a given vehicle, but the only automated data is almost completely limited to a parameter that specifies the position of the front plow on the truck. The information is binary in nature with the plow position either up or down. A simple switch monitors the position of the plow. Because of their simplicity the switches are not prone to failure; however, they are subject to considerable vibration and turbulent, corrosive environment, which does cause occasional failure of the switch or the connected wiring.

3.4. Vehicle operating parameters

Current vehicles may have as many as 70 separate electronic control units monitoring various subsystems of the vehicle. Most of these deal with the functional status of the engine, steering, brakes, suspension, electronics, etc. and the status of resources to sustain an operational state (e.g., fluid levels). But a number of parameters maintained on the vehicle bus offer the potential to provide information that could aid in the assessment of road conditions, either directly or through integration into other inference logic algorithms. The FHWA Connected Vehicle program is currently supporting a number of research programs to evaluate the feasibility of using vehicle bus information to support a variety of road weather programs. One key finding is that variables output from a single vehicle may not provide a fair representation of the conditions in a particular location. For example, the use of lights on and wipers on may be used as an indicator of the presence of precipitation. This assumption gains credence if multiple reports are the same from the same location; however, the output of these parameters from a single vehicle may represent that the operator merely forgot to turn the lights and wipers off or that there is no precipitation but spray from residual water on the road. Apparently, the use of indirect assessments of conditions will need to be part of a decision tree type of logic in order to integrate them into an automated road condition system. A few of the parameters that have are currently collected in the IMS programs and which could be integrated into potential road condition logic systems include:

- Vehicle speed
- Status of the light switch
- Position of the wiper control
- Miscellaneous engine parameters

3.5. Cameras

The installation of MDC controllers to support the AVL/MDC program provided a mechanism to capture the output from in-vehicle cameras and pass it along with the transmission of the MDC data. The vendors that provide the MDC systems have selected the cameras to be compatible with the controller unit they provide; therefore, the makes and models of the installed cameras vary. However, the cameras typically fall into the classification of dash cameras and are mounted on the dash or the location where a rear view mirror would be located in an automobile. The image resolution in pixel counts provided by three of the vendors is 640 by 480 and 320 by 240 by one vendor. The image capture rate is determined by each of the vendors and the update rate depends upon the data collection cycle used by each of the MDC vendor. Currently, the update periodicity is driven by the requirements of the MDSS programs, which update images at a 10-minute interval. All of the cameras used to this point are daylight cameras that capture light in the visible range.

4. MAINTENANCE DECISION SUPPORT SYSTEMS

From a broad perspective MDSS may be separated into five fundamental classes:

1. Mental rules, guidelines, and response scenarios based upon maintenance experience
2. Maintenance response nomagrams or guides
3. Manual of best practices
4. MDSS Prototype
5. Pooled Fund Study (PFS) MDSS

Expertise developed by maintenance personnel from years of experience has long been the primary form of maintenance decisions support. Practices that have proven successful become a compendium of guidance that is often stored in one’s head and passed from peer to peer over the years. Much of the information deals with practices that are effective and those that are not or which cause additional issues. The expertise of individuals gets shared and gradually is consolidated into Agency rules and guidelines. The guidelines are impacted by fiscal considerations and the raw treatment options are adjusted to compensate for costs, available equipment resources, and environmental considerations. For many agencies this first item in the MDSS list above remains the primary approach to MDSS and many supervisors manage their operations using the volume of information they have acquired through years on the job.

To assist new maintenance operators the rules and guidelines are sometimes summarized into a short set of treatment options or nomagrams illustrating treatment rates for different snow and ice control scenarios. These guides are typically laminated and placed on the dash or visor of the snowplows for reference as needed. They serve as guides for common conditions that are likely to occur but the guides are not normally composed to cover all possible situations.

Over the years some agencies did compose guidelines for the full gamut of scenarios that were encountered in winter maintenance. These guides became known as best practices and were specific to the agencies and local conditions. The guidelines tended to change over time as new maintenance techniques or treatment options were tested and introduced. In 1993, the FHWA initiated a research effort to create a "standard" set of best practices to address the evolving practice of anti-icing. The results were completed and published in June 1996 (1). The best practice guidelines addressed six weather event scenarios, including:

- Light snow
- Light snow with periods of moderate to heavy snow
- Moderate to heavy snowstorm
- Frost or black ice
- Freezing rain
- Sleet

For each weather event type there were recommended initial and subsequent response actions to deal with a set of input parameters that included:

- The pavement temperature and its trend
- The pavement surface condition status at the time of the initial operation

The recommendation options were also supported by a set of comments related to each set of input parameters that addressed special considerations for non-uniform conditions or changing trends in the weather event or road condition status.

The recommendations reflect actions necessary to obtain a high level of service and represented synthesis of best practices derived from DOT agencies throughout North America. Subsequent to the original publication the best practices recommendations have been updated and adjusted by many agencies to fit local policies and practices. It is important to emphasize that winter maintenance actions deal with a myriad of weather, pavement, and operational variables that uniquely impact the appropriate treatment response. The best practices approach aggregates nearly all of these variables except for the type of weather event, the pavement temperature, and the initial pavement conditions. Because the recommendations represent a response to a highly synthesized set of variables, they reflect an average response. The comments associated with best practices recommendations provide the user with guidance to more specific treatment options in special situations; however, the comments require user interpretation of the setting and some level of background in the potential effects of slightly different maintenance actions. Even with effective use of the comments, the best practices do not provide a specific response option for the exact conditions that may currently exist.

The FHWA had the federal labs develop the MDSS Prototype beginning shortly after 2000 to automate the generation of manual of best practices approach. The Prototype took point specific weather forecast information for a specific point along a route segment and used that input to run a pavement condition forecast model for that location. The output from the pavement condition model was used to project the initial road condition, the pavement temperature, and the projected change in the road condition over time to development the type of treatment action that was needed based upon the guidance from tables within the manual of best practices. The fundamental construct was the same as the manual of practice; the difference was the dynamic determination of the initial pavement condition class and the pavement temperature range. The weather forecast was used to derive the type of weather scenario. The Prototype was able to adjust the recommendations to some extent to integrate adjustments that were provided in the manual of practice. The Prototype was a step closer to being able to integrate the entire set of variables involved in winter maintenance snow and ice control, but did not fully address the complexities presented by each unique weather situation for the spectrum of potential operational configurations possible.

The most sophisticated approach to a MDSS solution was the PFS MDSS. In 2002 four agencies (North Dakota, South Dakota, Minnesota, and Indiana DOTs) came together to form the PFS MDSS Federal Pooled Fund Study. The ultimate goal was to investigate and utilize the scientific components of snow and ice control within the road. The key was to investigate the effects of chemical applications to the pavement the physics and chemistry associated with these interactions. The PFS MDSS takes into account past and current weather conditions, pavement conditions, and maintenance actions to make dynamic treatment recommendations based on forecast weather and pavement conditions. The PFS MDSS also utilized the Highway Conditions Analysis Prediction System (HiCAPS™) that takes into account the mass and energy.

5. EMERGING TECHNOLOGIES AND TRENDS

The fundamental process of capturing road conditions through visual observation and making these assessments of road conditions available to end-users has remained essentially unchanged over the last decade. Enhancements in the road condition reporting have predominantly progressed with improvements in communications, computer processing, and road weather sensors. The future enhancements of the program will continue to follow advances in these technologies. The two primary trends currently receiving the most consideration are:

1. the integration of additional communications and computer capabilities to create a complete, unbroken linkage from field observers to end-users, and
2. an automated field observation process that could potentially replace the requirement for human observers in the field.

The implementation of the two approaches represent disparate solutions and each follows a separate solution pathway; however, the evolving road condition reporting system will likely be a composite of the two approaches. This section reviews the emerging technologies and then discusses how these technologies will influence future trends. Sections 5.1 and 5.2 look at the communications and computing trends indicated in approach 1. Section 5.3 covers two emerging automation trends that have the potential to replace the current manual road reporting procedures.

5.1. Communications

Technological advances in the communications industry (in part, coupled with the rapid evolution in computing capabilities) have driven the major changes in road condition reporting over the last quarter century and particularly in the last decade. In particular, the transition to digital transmission of data facilitated the move away from voice transmission over analog communication resources. This was particularly augmented by the rapid growth of the Internet. However, rapid improvements in communications bandwidth and the introduction of cellular communications greatly aided this transition, since cellular communications provided a cost effective link between the field and the Internet communications backbone. The trend towards greater dependency on cellular communications will continue as the cellular networks become denser and more reliable. Thus, cellular communications has become a predominant mode for communications between field devices (data processing units and smart phones) and Internet portals. The Internet subsequently becomes the transfer medium to central facilities. Currently, this combination of cellular and Internet transport handles the majority of digital data transfer from ESS sites, MDC/AVL units, smart phones, and cameras.

The expanded use of cellular communications has also benefited from the development of a standard communication protocol and the introduction of enhanced mobile devices to communicate via the cellular networks. The current standard for wireless communication of high-speed data for mobile phones and data terminals is LTE (for long term evolution) and the manifestations of the standard in use are primarily third generation (3G) or fourth generation (4G). 4G LTE is based upon three predecessor network technologies:

- Group System for Mobile Communications (GSM)
- Enhanced Data rates for GSM Evolution (EDGE)
- Universal Mobile Telecommunications System (UTMS)/High Speed Packet Access (HSPA).

These were separate wireless telecommunications standards, each developed to support cellular communications in different parts of the world. A number of different standards such as the three cited vied for dominance as wireless communications developed. Another major protocol option developed in North America has been the code division multiple access (CDMA) standard used by Verizon and Sprint in the US and Bell and Telus in Canada. All of these organizations have now agreed to move to LTE and it is anticipated that LTE will become the first global mobile phone standard; however, different countries have allocated different frequency bands for cellular use so only multi-band phones will be able to use LTE universally. The LTE Advanced standard was formalized in March 2011 and was implemented in Russia in October 2012. LTE Advanced services are expected to appear in North America during 2013. The benefit of LTE Advanced is better use of communication topologies, which will permit a performance leap in wireless networks.

Twenty years ago radio communications and bandwidth limitations negatively impacted the ability to effectively move data from the field to central processing centers where it could then be consolidated, reformatted, and encapsulated into products designed to meet end-user needs. The introduction of cellular communications initially suffered from a lack of adequate cell towers, dropped connections, and significant costs for data transfer. However, the competition between the cellular companies forced rapid enhancements in cellular coverage and communications reliability. Lost communication connections and data latencies have mostly disappeared and technological capabilities within the cellular community now challenge developers to create new techniques to extract field information and make it available to the user community.

One non-cellular communications resource that has the potential to impact road condition reporting in the future is the dedicated short-range communications (DSRC) channel. DSRC is a medium to short-range communication channel designed to support automotive applications. In 1999 the Federal Communications Commission (FCC) allocated 75MHz of spectrum in the 5.9 GHz band for use for ITS services. To date DSRC has been primarily used to support operational ITS requirements such as toll collections. In addition, the FHWA has supported research into use of this bandwidth for a broad spectrum of applications, including:

- Emergency warning systems for vehicles
- Forward collision warning
- Intersection collision avoidance
- Electronic parking payments
- Commercial vehicle clearance and safety inspections
- Roll-over warning
- Vehicle to vehicle data exchange
- Probe and vehicle bus data collection

The FHWA Connected Vehicle program has invested a considerable amount of money and research into methods to collect information from private vehicles and statistically integrate this information into an estimate of the actual values for a number of parameters at a given point over a short period of time. Anything that can be derived from the vehicle bus could be synthesized into a single, best estimate value, but research thus far has focused on parameters such as air temperature, position of the wiper and light switches, differential slip, and vehicle speed. Once the research has proven the viability of collecting and processing these parameters, it will open the opportunity of establishing programs to instrument vehicles to collect road conditions and test whether automated road condition assessment techniques will provide acceptable results.

The communication of data within a government agency is typically accomplished through the use of wide area network (WAN) or local area network (LAN) conformations or a combination of the two. WANs are computer networking technologies used to transmit data over long distances and often between LANs. LANs are physically localized networks that use protocols such as Ethernet or Wifi to transport data. Many WANs are built by one particular organization and are private. Others, typically built by Internet providers, use leased lines to build the network and provide connection points to interface with LANs. Since dedicated leased lines remain relatively expensive options, WANs utilize packet switching techniques to optimize the use of the line. Network protocols such as the Transmission Control Protocol / Internet Protocol (TCP/IP) are utilized to handle transport and packet addressing functions. Protocols for data structure such as the National Transportation Communications for Intelligent Transportation Systems Protocol (NTCIP) used for transmission of RWIS data packets are designed to work within the TCP/IP framework.

The recent trend within government organizations is to extend the private nature of the state's network using virtual private network (VPN) functionality. VPN uses the Internet to extend its private network across public networks to connect remote locations. Agency computers can send and receive data across public networks as if the network links were part of the private network while still retaining all the security of the private network configuration. The use of Internet network infrastructure in lieu of dedicated leased connections provides significant cost reduction and permits communications at much higher data transfer rates. It is anticipated that the trend toward the use of VPN will become a more significant part of DOT communications in the future.

5.2. Computing

Advancements in computer technology over the past 50 years have transformed society from an industrial- to an information-based society. Ongoing technological advancements in computing and particularly mobile computing applications will not only continue this trend toward information sharing but also accelerate the process. There are many advances in computing that will drive the modifications to the road condition reporting system architecture to increase its efficiency and value, but the two factors that most likely have had the most impact are compute speed and data storage. Road condition observations submitted in the field as digital codes will be converted almost instantaneously into presentation formats and messages understandable by users and delivered directly to or made available to these end users without delay other than quality control filters.

5.2.1. Enhanced Road Condition Reporting Techniques

Road condition observations made in the field that are still submitted by voice communications via a radio interface in most agencies, will be converted to digital communications and transferred via networked communications directly into the road condition reporting system. The first stage in this process will result from applications on mobile devices in the vehicle. This capability already exists in a number of MDC/AVL units where the MDC applications on in-vehicle computers permit touchscreen entry of road condition observations. Similar applications are appearing on tablets and smart phones. The obvious concern with the input of data via touch screens is safety, since the manual actions necessary to enter data via these applications require drivers to divert their attention from the road if the information is entered while driving. This safety issue is likely to be overcome by the use of automatic speech recognition (ASR) techniques. ASR is already in use in some automobiles and commercial vehicles and the technology is being refined rapidly. The ASR challenge in snowplows is noise interference. Acceptable solutions will require a design that filters all extraneous noise and allows the voice input of the driver through without the use of any cumbersome device that restricts free motion of the driver or is unacceptable to drivers. ASR techniques coupled with the automated transmission of the digital data will be the first stage. However, this one-way solution will quickly be transferred to interactive voice response (IVR) services for full communication from vehicles in the field to other communications devices and agency personnel. The ultimate solution will be a completely hands-free solution for in-vehicle communications systems.

All agencies using field observations as a basis for their road condition reporting system will move to either a road condition reporting solution that exists as a single software package or a composite of linked software applications that execute parts of the end-to-end transfer of road condition information. The software solutions will permit a direct transfer of information from the field to end-users with minimal delay in the transfer process. The only tangible delay will occur where states require oversight and approval of the field observations prior to release to the public. The use of road condition observations from the public has gained acceptance in some states recently and it is anticipated that there will be a growth in the number of programs that permit approved citizens to submit observations to supplement the ‘official’ observation set. Government approved involvement in the reporting process may become a necessity to counter a proliferation of observations/comments via non-government social media programs. On the user end of the road condition transfer process, IVR capabilities will continually be improved. Part of the improvement will involve greater consistency in the synthesized voice output and better integration of local pronunciations. IVR support will also improve to provide an interactive delivery of information to travelers. Current road condition reports address conditions along a specified segment of highway. Travelers may not be familiar with the demarcations set by the advanced traveler information system (ATIS, typically known as 511) but would rather get the road condition guidance referenced to points they know. ATIS systems will develop algorithms to translate the specification of road conditions for ATIS-defined segments into a more dynamic capability for road condition retrieval. This capability will also be an important consideration for higher resolution or shorter segment road reporting.

Another significant trend related to computing capabilities is the development of mobile applications for use on laptops, tablets, and smart phones with particular emphasis on the exploding market for applications on smart phones and tablets. It is likely that smart phones and tablets will have similar capabilities as existing laptop and desktop computers within the near future. The screen size of these mobile devices will remain smaller than laptops and tend to limit the amount of information that may be displayed on one screen; however, pixel resolution of these devices is increasing rapidly making it easier for the user to interpret graphical displays. Thus the use of icons will replace some of the text and the ability to quickly move the displayed image with simple hand movements will offset the smaller viewing area. Currently, interaction with the devices is accomplished using the touch screen or keypad; however, in is anticipated that IVR capabilities will become more fully integrated into these mobile devices in the near future and users will interact with the phone or tablet using voice commands. The voice interaction will impact both the field and end user interactions. Smart phones or tablets will become another medium for input of field observations in a hands-free mode. Likewise, at the end-user’s end smart phones and tablets with IVR capability and the ability to recognize speech commands will permit travelers to interact with 511 services in a completely aural mode.

5.2.2. Automated Road Condition Reporting

Potentially the biggest change to the road condition reporting program may come from processing data collected automatically by sensors in the field and synthesizing this information into feasible representations of existing road conditions. The techniques used by the human mind to visually assess the conditions along a highway segment and translate these observations into a road condition class are quite complex. To duplicate the human observation process with sensing devices will require improvement in the sensing devices and the logic that synthesizes multiple observations into a resulting road condition specification. Software already exists to perform data fusion from available sensors and data sources and derive road condition classes (e.g., MDSS); however, current technology is not able to reliably produce an equivalent set of road conditions as the present human observation technique. Current road condition observations are an integration of a large set of independent observations performed over a length of highway during an undefined period of time. To duplicate this process using automated sensing devices will require:

- the collection of output from a suite of sensors at relatively short intervals along a highway;
- the derivation of the road condition at each of the data collection points; and,

- a statistical integration of the individual results into an average, median, or worse case road condition state.

The current challenge is that a number of the existing sensors in use to support RWIS and/or MDC/AVL do not capture data in the necessary format or level of accuracy needed to correctly model the road condition status at each discrete sample point. Experience indicates that the road condition modeling techniques used in MDSS are adequate to transform accurate input data into the correct representations of the road condition. But it is imperative that the input be accurate, reliable, and timely. Thus, the priority in the development of sensing capabilities is the introduction of new or modified sensors that provide measurements with the accuracy and reliability needed to support road condition modeling techniques. The computation of road conditions at multiple points along a segment will require substantially more computer processing than a single representative point for an extended segment of highway that is currently used. It is anticipated that improvements in processing power will offset the increased processing load needed. The computational capability and capacity will likely be adequate to provide automated road condition assessments; the question is whether sensors exist or are in development to measure the conditions needed to support the automation process.

5.3. Integration of new mobile sensors

A road condition reporting system based upon the total automation of the data observation techniques with the exclusion of human involvement may be accomplished in two different ways. The first approach is the use of a specific sensor to perform the visual assessment currently performed by observers. The second approach is the integration of the output from a number of sensors and the use of decision logic or modeling technique to derive an assessment of the appropriate road condition class. In reality, the second approach is somewhat similar to what the human mind does to observe and specify road conditions. The requirements to support the two approaches differ, thus the discussion of direct measurement techniques and the integration of multiple sensing sources are treated separately.

5.3.1. Direct measurement of road conditions

The direct measurement approach assumes that the output from one sensor or a small integrated group of devices is adequate to generate and average the road condition observations for a given roadway segment. No further information would be necessary. There are two mobile sensing options that have the potential to provide this capability: mobile road condition sensor packages and cameras.

The existing road condition sensing packages manufactured by Vaisala and Teconer and the new sensing package to be released shortly by Lufft represent the direct unitized packages for measuring road conditions. They all employ non-contact sensors that are placed on a mobile platform and routinely report part or all of the following conditions:

- Road condition
- Thickness of the layer components
- Temperature of the road surface or the upper surface of the materials atop the road
- Grip
- Air temperature

- Dew point temperature
- Relative humidity

These sensors view the accumulation layer from above, thereby sensing conditions in a way similar to that of a human observation. The sensors provide an assessment of the water, snow, and ice depths and from the computed percentage of mass of the components yield the following road condition classes: dry, damp, wet, snow, and ice. As of yet they have not been configured to provide the road condition classes of slush, packed snow, drifting snow, frost, or sleet/hail. The sensors provide a measure of the depth of ice, snow, and water to the depths stated within the stated depth range in their specification documentation. The depth of the actual components in real life situations does exceed the maximum depth capability of the sensor at times. In that case, the sensor provides guidance on the top surface of the accumulation layer.

Since the sensors have only recently been introduced to the market, there are minimal published third party test results in the literature. The Finnish Transport Agency released a 2011 report on friction meters, which included the Vaisala mobile DSC111 and the Teconer RCM411 sensors. An English translation of the original report published in Finnish may be found at http://www.teconer.fi/Friction_Meters_2011.pdf. The study compared the output of friction from these two optical sensors versus the friction obtained from a group of sensors that use classical decelerometer or variable slip techniques to measure the braking friction. The two non-contact infrared laser sensors did not reliably duplicate the friction values provided by the older friction deceleration measurement techniques. Since the optical sensors derive friction or grip from the measurement of the depths of snow, ice, and water and/or the composite of these components, there may some uncertainty in the friction output when the accumulation layer depths exceed the sensors' maximum measurement depths. The other unknown is the ability of the sensors to provide a consistent output is the harsh operating environment of a snowplow or supervisor's truck. Visual obstructions due to an accumulation of snow or displaced snow, slush, or liquid spray and vibration may be issues that impact sensor performance.

Nevertheless, these optical sensors offer the greatest potential to measure road conditions in an automated manner. Competition is likely to spur improvements in the sensors and measurement technologies that gradually resolve the early issues noted with the sensors.

Cameras mounted within the vehicle cab offer another solution to automate the road condition observations. However, this will require the development of image analysis techniques that utilize the visual characteristics to assess road conditions described in section 2.5. Image analysis techniques have been developed for a number of traffic applications recently and the improvement in dynamic image analysis is a rapidly evolving technology. It is likely that the assessment of road conditions from a stationary platform will occur in the near future; however, the ability to monitor and assess conditions in a continually changing reference frame may require additional time and processing power. The approach has an advantage over the non-contact infrared road condition sensors since it also has the potential to see weather conditions and certain road condition situations such as packed snow, slush, drifting snow, and frost that road condition sensors cannot differentiate.

It is quite possible that the eventual solution will require the integration of both techniques.

5.3.2. Modeling road conditions

Modeling road conditions requires a technique that integrates the mass flux of snow, ice, water, frost, and treatment materials onto and off the pavement; changes in state of water (ice, water, and vapor); the horizontal movement of snow and slush; occasional events such as flooding, avalanches, or vehicular transport of snow; the application of treatment materials; and the effects of traffic. Because the water molecule can exist on a the pavement in its liquid or solid state and change between these states depending upon the heat flux into and out of the accumulation layer, a road condition model also must have information regarding the temperature of the layer and the heat exchange between the layer and its environment. Maintenance decision support systems are built around such a model and depend completely upon the proper simulation of the input parameters and the mass and heat changes that occur in the accumulation layer. In order to properly model road conditions, the system must establish the characteristics for an average slab of pavement, its construction base materials for each segment of highway, and the lane configuration. The model also requires an estimate of the daily traffic volume per lane and the distribution of traffic loads hourly during the day. On a dynamic basis, the model must routinely receive input of the following parameters at one or more points in the highway segment to generate the road condition and the pavement temperature:

Precipitation type	Precipitation amount
Air temperature	Dew point temperature or RH
Wind direction	Wind speed
Solar radiation flux (or cloud cover)	Net radiation balance (or cloud cover)
Time of plowing	Time of material treatment
Material application rate	Type of material being applied
Surface character of surrounding snow	Depth of snow in fields surrounding highway

The weather parameters in the list above need to be updated at least once per hour or less. The treatment actions need to be updated as the action occurs. The model generates the pavement temperature, road condition classification, and the depth of water, snow, compacted snow, frost, and ice. It also keeps track of the amount of chemical in the accumulation layer. Although the model can function using input from the listed parameters, it can benefit from actual input of the pavement temperature and the observed road condition status from RWIS sensors and/or MDC observations.

An automated solution built upon a modeling technique, such as MDSS, will require a data source for each of these parameters. The following sections review the sensors that are necessary to construct such a solution, feasible ways to collect the required information, and challenges associated with the measurement of the desired data to support an automated model.

5.3.2.1. Precipitation type and amount

Prior to 1980, the precipitation type was collected visually and the amount of precipitation was measured either visually or by mechanical devices such as tipping bucket or weighing gauges. In the 1980s, the National Weather Service integrated an optical weather identifier that automated the measurement of precipitation type and near-instantaneous rate of precipitation. The RWIS program integrated this type of sensor into its suite of sensors starting late in the 1980s. The technique used by these weather identifier sensors was the measurement of the terminal velocity distribution of hydrometeors (water droplets, snowflakes, or forms of ice) and the number of these hydrometeors within specific terminal velocity ranges passing through a volume of air in a specified period of time. Because snowflakes, ice, and water all have different terminal velocity ranges, the measurement of terminal velocity was used to determine the type of precipitation. Since terminal velocity of a hydrometeor is proportional to its mass, it is possible to compute the product of the mass times the number passing through the volume per unit time to get the precipitation rate for that interval. If the rates for short sampling periods are summed over a longer period (say one hour), the result is the accumulation in that period in liquid equivalent. The original sensor developed for the National Weather Service to replace the rain gauge and allow measurement of the type of precipitation automatically was called the Light Emitting Diode Weather Identifier (LEDWI). The manufacturer of the LEDWI subsequently created two similar instruments for the RWIS program called the Optical Weather Identifier (OWI) and Weather Identifier and Visibility (WIVIS) sensors. These instruments used a scintillated beam of light to sense the presence and fall rate of hydrometeors. Thies, Vaisal, and Ott Messtechnik have also developed laser-based approaches. Lufft took a different approach and addressed the detection and fall velocity of hydrometeors by using a radar technique to sense the terminal velocity and the number of hydrometeors per unit time.

All of these sensors perform reasonably well when maintained properly. Their limitation for this study is that each sensor must be installed at a fixed location and remain stationary; they will not perform properly on a mobile platform.

Providing an accurate amount of rain, snow, sleet, ice pellets, or hail is essential for a mass balance model; thus it is important that any precipitation instrument used to support a modeled assessment of the road condition at a point along a road segment must be able to accurately and reliably measure the accumulation of precipitation over a period of time. This is absolutely critical in determining the amount of snow that falls on a highway segment as a function of time. Even if a mobile sensor could determine the precipitation type and rate as it moved along the highway, it would be unable to determine the accumulation of the precipitation at a given representative point on the segment. The inability to measure precipitation accumulations at given points along a segment of highway is one of the significant limitations for road condition models. Currently, radar estimates are used to estimate the precipitation, but this technique has to deal with a number of deficiencies, such as noise in the radar returns, false returns, and voids in the radar pattern between radar sites. The ultimate answer in the support of the road condition modeling requirement would be a network of precipitation sensors that measure the precipitation type and amount for a significant share of the route segments.

5.3.2.2. Air temperature and dew point temperature

There are a number of quality air temperature and RH sensors that will provide creditable observations from a moving vehicle and this information can then be provided to a road condition model to support the modeling of road conditions at any point along the highway segment. Temperature tends to change relatively slowly with time and distance so temperature values sampled at intervals along a route can be used in conjunction with temperature observations from other vehicles or stationary sources to create a consistent picture of the air temperature over an area. Dew point temperature is also relatively consistent and will only vary appreciably when there are moisture sources nearby. The one concern with temperature and RH sensors on a vehicle is the microenvironment that develops around a snowplow actively plowing snow. A buildup of snow around the sensing device can restrict the free flow of ambient air across the sensor temporarily impacting the temperature and dew point temperature readings. The cloud of snow around the plow also creates an environment that likely has a relative humidity that is higher than the surrounding air.

5.3.2.3. Wind direction and speed

There are a number of different sensor designs to measure wind speed and direction from a stationary platform but a very limited number designed to work on a moving platform since the computation of wind speed and direction must be able to subtract out the vector speed of the vehicle. Because vehicles traverse curves or make turns the computation of the correction vector is tricky. Further, turbulence caused by other vehicles, plowing actions, and structures in or along the right-of-way disrupt the normal wind field in the highway environment. Therefore, efforts have not been made to market vehicle-mounted anemometers and use them operationally.

5.3.2.4. Solar and net radiation

The amount of solar radiation reaching the pavement during the day and the net outward radiation at night have significant impacts on the pavement and accumulation layer temperature and therefore the state of the road condition. Thus, radiation is a dominant factor in the heat balance equations in road condition models and the models require some form of radiation information to provide accurate estimates of the road condition state. Sensors to measure solar and net radiation need to remain horizontal and would need to extend out away from the vehicle to monitor the net radiation factor. There are a number of excellent sources of radiation sensors, but all of the solutions will need to be placed on a stationary platform.

5.3.2.5. Time of plowing

Knowing what maintenance actions are performed and when they took place is critical to modeling the correct road condition for a segment of highway. Plowing removes a considerable amount of the accumulation layer mass; therefore, it is essential to know when a snowplow passed a given location and whether plowing was occurring during that pass. The current model used in the PFS MDSS simulates both the cross-sectional and vertical distribution of snow, compacted snow, ice (frost, crystalline, and amorphous), and liquid components. The liquid component contains water and dissolved deicing chemicals. The model removes the top portion of the accumulation layer to a specified depth, thereby removing the mass of those constituents expected in the distribution. Since the liquid component gravitates toward the base of the layer, the liquid and dissolved deicing materials tend to be near the bottom of the layer. Compaction processes create a snowpack zone next to the pavement and refreeze occurs in the wheel tracks usually in a thin layer near the pavement. These factors affect what material remains beneath the plow depth and determines the most probable state of the road condition after plowing. However, without the plowing information the model overestimates the depth of the accumulation layer and will likely report an incorrect road condition. Thus, an automation approach to road condition assessment using modeling techniques must have reliable information regarding the plowing activity of every snowplow in the maintenance arsenal.

5.3.2.6. Application of materials

Reliable input of the application materials being spread on a given segment or portions of that segment is critical to effective use of a modeling technique for road condition reporting. A model requires information regarding the type of material applied, the rate of application, the location of the application, and when the material was applied. This information is available from MDC/AVL units using both touch-screen input and output from ground speed controllers. However, the evolving MDC/AVL solutions have several limitations or deficiencies, specifically:

- The inability to accurately indicate the specific geospatial
- No mechanism to assure that the material type has been updated to match the materials currently loaded for application
- Operational issues with the distribution systems.

The geospatial resolution is partially due to the accuracy of the GPS units on the vehicles and partially due to registration issues with the GIS maps that show the location of the roadways. Many of the maps in use today have highway locations that are sufficiently inaccurate to permit placing a vehicle icon at the exact location of the vehicle report on electronic displays. This resolution discrepancy particularly impacts the ability to determine which lane the snowplow is servicing. Most GPS units today are accurate to within 3 meters and many of the GIS maps have accuracy errors of this magnitude or greater. With ionospheric correction capability the accuracy can be increased to centimeters. The GPS modernization program is adding new signals and frequency options for non-military use that will permit location accuracies in the centimeter range. This should improve GIS registration and vehicle location capabilities to adequately provide the level of geospatial definition needed to support road condition modeling.

Current MDC/AVL systems with touch-screen input have the ability to indicate the type of material and often the spread rate. For convenience the last entered material type and application rate remain as the default for each subsequent application run. Drivers sometimes forget to change the default setting when a new material is loaded and the road condition model subsequently uses the wrong material or rate in its computation of the resulting road condition. If the modeling approach is to be used to create road condition reports, then a mechanism will need to be employed as part of the process of loading treatment materials or at the start of each run to assure that the MDC controller has the correct material in its memory for use on that run. The material type will need to be done via a voice command or keyed-in input prior to initiation of the application run. It may be necessary to establish a confirmation control step to assure the run starts with the correct material specification.

Issues with the performance of the distribution system are outside of this study but will be gradually resolved as the DOTs and spreader controller manufacturers work together to eliminate or minimize issues associated with hydraulics and material clogs.

5.3.2.7. Character of blowing snow source area

Residual snow resident across the landscape following a snowstorm has the potential to be picked up and transported by winds in excess of about 15 mph. For some areas of the country blowing snow is the predominant winter maintenance issue; therefore, a road condition reporting system based upon modeling technics must have a source of information on the amount of snow surrounding the highway network and the degree of crusting of the top surface of the snow layer. With a good knowledge of the potential for the snow to move or saltate and a good measure of the wind speed and its nominal direction, a model can estimate the amount of snow likely to move horizontally across the pavement and determine its potential to deposit on the roadway or be captured in the wheel tracks by passing vehicles or by residual chemicals.

Blowing snow can be observed from the cab of a vehicle but there is no routinely used instrumentation to measure the horizontal flux of snow. It is possible to use optical methods to measure the transport of snow or ice crystals through a vertical plane parallel to the highway, but this must be done along the side of the roadway and typically near the fence line. No sensors are currently marketed to provide this measurement and any information gained would only be representative of the conditions at the site of the sensor. The resource currently used to model the potential for blowing snow is a data set maintained by NOAA's National Operational Hydrological Remote Sensing Center that estimates snowfall nationally and attempts to model the water content and characteristics of the snowpack. This remains the best resource to satisfy this modeling requirement.

5.4. Forecasted road conditions

Techniques currently exist to project road conditions into the future based upon forecasted weather conditions; these techniques have been used by most DOTs for a number of years to support their decision support requirements. The same modeling practices could be used to aid in the automation of road condition reporting. The challenge in the use of these techniques will be to achieve the level of performance accomplished with the visual observation procedures in use today. The methodologies used in determining the observed road conditions as described in section 2.5 are quite complex and require sophisticated observations and the integration of a number of separate observed parameters to derive the final observed road condition. In order to emulate the observation capabilities of the human-based observation system and forecast the probable road conditions for the future will require three essential components:

- A way to assess current conditions accurately and reliably
- A dynamic, accurate, and reliable understanding of maintenance activities tied to a given segment of highway
- A detailed and accurate weather forecast that can be adjusted for rapidly changing weather conditions

The key factors needed to accomplish the three fundamental requirements include:

1. A simulation technique that effectively integrates <u>all</u> of the factors that impact road conditions
2. Accurate initialization of current road conditions
3. An accurate forecast of all of the meteorological parameters that impact the mass and energy terms of the simulation model

4. Proper characterization of the road construction features of the road segment and the sub-pavement profile
5. A route segmentation procedure and processing technique that generates a composite of the conditions along reporting route segments
6. Consistent, repeatable operational maintenance treatment patterns and/or a dynamic system to adjust the maintenance patterns to reflect current operations on that segment
7. Accurate traffic volume and speed statistics
8. An accurate assessment of the snow cover and the characteristic of its density and surface state
9. Characterization of the topography, vegetation pattern, and structures along and adjacent to the route segment

Under different weather scenarios or even within a given event each of these factors may significantly influence the road condition forecast. The concern in the development of a forecast system is what can be done to minimize the negative impacts, which may occur due to inconsistencies or lack of information associated with each of these factors. The following subsections look at each of the factors and ways to minimize performance deficiencies.

5.4.1. Simulation Technique

The simulation technique will need to provide as complete a simulation of the effects of each factor that is known to affect road conditions as possible. Existing knowledge of how different factors impact road conditions must be transformed into accurate simulation logic. Estimation techniques must be minimized as much as possible. An example might be appropriate to aid understanding of the level of simulation recommended. It is known that traffic plays a significant role in working treatment materials into the accumulation layer and changing the physical configuration of the accumulation layer. A simple, parameterized approach to traffic would use AADT distributed to fit its normal hourly distribution pattern to estimate the influence on road conditions. But in reality, the accumulation is continually in a state of flux based upon precipitation patterns, treatment activity, and the influence of vehicular traffic. Traffic creates distinct cross-sectional topologies in the accumulation layer, moves different materials in various directions based upon the state and consistency of the accumulation layer, removes materials from the accumulation layer (primarily due to splatter and spray), mixes the constituent materials in the accumulation to redistribute chemicals and change their rate of deicing effectiveness, add some heat to the wheel track region, etc. All of these factors are interrelated and dependent upon the level of traffic in given time interval. Since the accumulation layer is continually in a state of flux during a winter event, the influence of traffic has different impact for each unique situation. Being able to integrate the proper traffic volumes, speeds, and tire distributions is critical in evaluating the most probable current conditions as well as projecting forecasted conditions. Traffic represents only one factor. All of the other input variables must be treated with similar detail.

5.4.2. Accurate initialization of current conditions

Accurate initialization is an absolute requirement for the generation of forecasted road conditions. If a simulation process starts with an incorrect assessment of the current conditions, the projections going forward and recommended treatment actions have a high potential to be incorrect. Existing pavement condition models provide an accurate representation of the road conditions on a given roadway segment IF the correct conditions that have or are impacting that segment are correct. The most critical input parameters that must be dynamically provided and input accurately are the observed or extrapolated weather conditions (particularly precipitation type and rate), treatment actions, resource allocations, and traffic. This requirement puts a huge emphasis on the monitoring capabilities and methodologies discussed in section 5.3. In addition, MDC/AVL units must provide the actual treatment information to allow pavement condition models to correctly simulate the existing road conditions or projections of future road conditions will suffer. In order to make MDSS and its indigenous pavement forecast model a viable approach to an automated road condition system, it will be necessary to assure that all vehicles that treat a segment of highway where an automated road condition system is in place have an accurate and reliable MDC units or some system to report actual treatment activity.

5.4.3. Accurate weather forecast

The weather forecast is typically not as critical to the performance of a road condition forecast system as is the correct initialization of the current road conditions. While an inaccurate forecast may not yield a bad projection of future road conditions, the impact of a bad forecast is partially dependent upon which parameter(s) turn out to be inaccurate. Unless they become critical factors in a specific forecast, parameters such as air temperature, wind direction, and visibility may not induce much error in the projected road condition. However, the correct forecast of the occurrence of precipitation, its type, and the rate are critical. Likewise, in certain scenarios the radiation fluxes, dew point temperature, and wind information can have important impacts on the projected road conditions although in most situations small errors in the forecasted values will not appreciably affect the forecasted road conditions. Precipitation is the critical parameter in the forecast and because precipitation often varies over short distances or occurs as snow bands, showers, or isolated events it becomes critical in the modeling approach to adjust the forecast to project these local patterns as well as possible.

5.4.4. Characterization of the construction profile

The heat energy balance of the pavement at any point in a route segment depends upon the proper parameterization of the physical character of the pavement and its substructure. Since the heat flux at the top surface of the pavement affects the state of accumulation layer it is important that the parameterization of the structure and materials in the pavement slab and the profile beneath the pavement reflect the actual conditions for that road segment. One of the issues that the road condition modeling will need to deal with going forward is how to characterize the different pavement materials and profiles over a segment of highway. Currently, the pavement forecast models use an average set of profile conditions; however, there may be unique sections of highway that have considerably different construction, overlay, patching, or sub-pavement profile conditions that create local zones that induce adverse road conditions that do not fit the wider average profile.

Bridge decks and elevated structures also create unique environments that are prone to adverse conditions that do not exist across the larger extent of a given segment. Yet these atypical short segments may develop adverse conditions in certain winter scenarios that need to be reported and/or projected in road condition reports to adequately warn motorists of potential areas of concern.

5.4.5. Route segmentation procedures

The survey performed on road condition reporting indicated that most DOTs report the worst conditions along the segment of highway rather than the average conditions. This infers that an automated analysis and forecast system will need to be designed to compute conditions for the one location that habitually has the worst conditions if the process is to continue generating conditions for one representative point on the segment. The alternative would be to divide a road segment into sub-segments and compute existing and projected conditions for each sub-segment and then develop a technique to consolidate the results from the sub-segment back into a report for the larger segment. One of the trends that is evolving out of the Connected Vehicle program and advances in Smart Vehicle functionality is the potential to provide sub-segment processing and deliverable information to guidance systems that can advise drivers of impending issues they are likely to face and how far in the future or down the road. Processing power and the cost of communicating the huge amount of data is the current constraint to moving to greater sub-division of highway segments, but the road condition automation requirement will require better definition of localized conditions that impact driving.

5.4.6. Maintenance patterns

One of the limitations of road condition forecasting deals with the necessity to project the anticipated treatment actions. Current approaches assume that maintenance actions follow a routine cycle performed by a single vehicle assigned to the route that starts at the local maintenance facility, performs maintenance actions along the specified route in an out-and-back cycle, and returns to the maintenance facility prior to executing the next. The basic treatment pattern has been modified to permit more than one vehicle on certain routes and the execution of irregular maintenance patterns that still function in a modified out-and-back manner. A route management routine is needed that will permit non-standard treatment options, such as patterns that plow and treat ramps, rest areas, shoulders, and extensions off the primary route. This capability needs to be coupled with the route segmentation modifications discussed in section 5.4.5, because these patterns create differential treatment patterns within different sub-segments of the defined maintenance route. The segmentation would also deal with overlap sub-segments where vehicles leaving and returning to the maintenance facility share a common section of highway, which may get treated differently by different vehicles at different times. It is anticipated that the GPS capabilities within MDC/AVL units will improve and the MDC controllers will provide more detailed information regarding the exact application rates for specific road segments and lanes at the appropriate time. Thus one of the trends that will impact road condition analysis and forecasting capabilities is knowledge of the actual patterns that a given vehicle has performed, its current position, and the most probably ensuing maintenance pattern based upon historical patterns. A more attractive solution would be the development of a supervisory control function that would permit the driver or supervisor indicates the next planned treatment pattern(s).

5.4.7. Accurate traffic information

As discussed earlier, traffic can play a significant part in maintenance actions. Not only does traffic work to influence the character of the accumulation layer, but it can impact the ability of a maintenance fleet to efficiency and effectively treat roadways. As the density of traffic monitoring systems continues to increase, the understanding of traffic patterns will increase. This will provide a better projection of traffic loading at specific times and the anticipated periods of congestion. Most of the traffic data thus far is generic and is not conditional upon external factors such as specific weather scenarios. Major metropolitan areas are looking for methods to project traffic patterns and volumes during adverse weather situations. Such knowledge will allow them to adjust treatment actions to deal with anticipated congestion periods when they are not able to effectively treat roadways.

Even where congestion is not an issue the use of real time traffic information can be integrated into the analysis of current road conditions and scenario based traffic speed and volume information may be projected forward and integrated into the pavement forecast model.

5.4.8. Snow cover analysis

Blowing snow is the most significant winter weather condition that a number of states must address on an annual basis. Several models exist to project the potential for blowing snow. Each of these models requires a good assessment of the snow cover in a given area and the condition of that snowfield. The depth of accumulated snow is important, but the surface state of the snow cover may influence whether the projected winds will erode the existing snow cover and move it horizontally. Snowfall plays a major role in creating the source for blowing snow but the existing resources available to determine snowfall at a spatial grid necessary to support an accurate estimate of snow cover depth don’t exist. A better program to measure snowfall will be an important factor in estimating the source field for blowing snow and projecting how the snow will respond to the forecasted weather conditions and in particular the winds. Such a snowfall measurement program may be a function that is external to maintenance and road condition reporting activities but is a resource that will greatly improve road condition reporting.

5.4.9. Topography, vegetation, and structures

The proper analysis and projection of blowing snow is highly dependent upon a detailed and current analysis of the topography, vegetative cover, and structures adjacent to the highway. This information is critical input into the blowing snow models to define sections of highway that are prone to blowing snow and properly analysis and project blowing snow in these areas when conditions exist that will support the transport of snow. These three factors work together to either decelerate winds causing snow to accumulate in drifts or to funnel and often accelerate the winds to increase blowing snow conditions. Currently, vegetative cover maps exist but they are general in nature and are not updated routinely. Small changes in the vegetation left at the end of harvesting can cause substantial changes in the drifting conditions locally. To improve the forecast of blowing snow conditions it will be necessary to improve the specification of vegetative cover, the presence of buildings and related structures, and how these features most likely will impact wind flow during different surface wind patterns.

5.5. Trends in integration of these technologies

5.5.1. Communications

Communications will continue to change at a rapid pace and along with computing techniques drive the development efforts of an automated road condition reporting system. Cellular technology will progress in several ways. The cellular coverage area will move towards 100% as the network of cellular towers expands for the various carriers and data compaction techniques will improve data exchange rates as new versions of the communication protocols are introduced. The consolidation of the industry on one standard protocol will accelerate the effort to make this standard protocol as efficient as possible.

The increase in communication speeds via cellular will also drive the development of more powerful mobile devices, such as smart phones, tablets, in-vehicle communications devices, and new devices that integrate communications technology into small objects that people commonly carry (e.g., watches, eye glasses). These smart, mobile devices will become intelligent communications centers, using IVR and localized data processing applications to convert verbal input into logical commands and initiating the appropriate response. The applications on the communications devices will interact via cellular with remote computer applications to acquire and retain a dynamic knowledge base in the background, which will then permit a user to state a request to the device and get an immediate response with the appropriate guidance. Applications will gain intelligence about what information is crucial to the user and gather this information prior to the user's request. For new or one-time information requirements the mobile devices will convert the request to a digital query and acquire the information from the appropriate source. Information that users currently acquire using a keyboard and web browser or other computer application will become routinely accessible via voice commands. The deliverable will be either through standard visual means on the device or voice synthesized answers. IVR speech capabilities will improve to the point where it will be difficult to ascertain if you are interacting with a person or a device.

The Connected Vehicle program will continue to expand and look for an appropriate mechanism to communicate information vehicle to vehicle (V2V). It is not certain whether data will be exchanged V2V or via vehicle to infrastructure (V2I) and back to other vehicles. The focus so far in the Connected Vehicle program has been development of the infrastructure to acquire information from the vehicle bus and communicate that information to other vehicles. It is likely that the applications and techniques being developed for mobile devices that use cellular communications will get integrated into the DSRC communications approach and cause the two separate development efforts to merge towards one another. That would suggest that digitized verbal communication between vehicles is a possible direction for the Connected Vehicle program.

The increase in bandwidth over WAN topologies will increase as data exchange protocols become more efficient and as distributed processing and data storage solutions evolve. The demand for rapid retrieval of data from Internet sources will support ongoing research and development to create more effective ways to move data more efficiently. Since data communications is intimately tied to processing speeds, it appears that Moore's law will remain valid going forward and that processing speeds will continue to increase exponentially. This will lead to increases in the data transfer rates and ability to considerably increase the amount of data exchanged via existing and expanded networks.

5.5.2. Computing

Computing speeds will continue to increase based upon hardware improvements and processing techniques. This will support greater efficiency and compute capabilities in computer programs that require extensive data processing. MDSS is an example of this type of program, thus the increased processing capabilities will provide the resources to continually update road condition analyses and forecasts and increase the number of segments used in a pavement condition simulation system.

A more dominant trend in computing appears to be a move toward miniaturization of computing devices and an emphasis on more mobile data processing devices. The convenience of being able to acquire and process data at any location is becoming a market requirement; therefore, it is likely that these devices will become a bridge between the user and the larger processing centers. The mobile devices will become an interface to the more extensive data processing centers and appear to have the momentum to replace laptop and desk top computers as the user’s interface to applications running on large computer configurations. The miniaturization process will push the development of computing capabilities on devices not used directly as computing platforms in the past. Smart phones and tablets will integrate more computer capabilities and develop all of the capabilities as existing laptops and desktops. Computing capability will be integrated more fully into cameras, appliances, bus structures in vehicles, and devices normally carried by an individual such as watches. As indicated in the communications section, computing capabilities will be integral in the development of an intelligent communications center within a vehicle that will become a mobile information resource for individuals in the vehicle.

5.5.3. Sensor Technology

Improvements in sensor technology used to measure environmental parameters will occur slowly for devices used to support road condition reporting requirements. The reluctance to expend considerable research funds on the development of new and improved sensors reflects the limited market to support this research. Nevertheless, efforts will continue to improve the ability to determine road conditions using infrared laser technology through refinements in the sensing techniques. This development effort will increase if the non-contact sensors are proven to be an accurate and reliable source of information regarding road conditions and are accepted within the DOT market.

Cameras appear to have the greatest potential for deeper utilization in the transportation market and as a resource for road condition assessment. Image analysis has grown rapidly in traffic management. The techniques used to determine the presence and type of vehicle, motorcycle, bicycle, other form of wheeled vehicle, and even pedestrians are similar to the image processing necessary to assess the state of the accumulation layer and the weather conditions and transform this into a road condition report. The introduction of an effective road condition image processing capability would provide a significant boost to the automation of road condition reporting. It is anticipated that the first step will be the ability to perform this type of image analysis on stationary cameras. If the technique can be employed on the imagery from existing cameras, the road condition monitoring program has the potential to expand rapidly.

5.5.4. MDSS and Road Condition Forecasting

Road condition forecasting will continue to be dependent upon improvements in monitoring and reporting systems associated with weather and maintenance treatment activities. MDSS requirements for observed weather require a considerably denser network of observations than what currently exists. Additionally, the network of observations systems must be able to provide relatively accurate and very reliable reports of precipitation type and rates at reporting intervals on the order of once every 10 minutes. This exceeds the capability of most of the National Weather Service sources. It will be critical to develop a precipitation analysis network that can aid the current radar resource and fill in holes or resolve anomalous echo reports inherent in radar technology to yield an accurate spatial analysis of the precipitation pattern. The analysis is paramount to creating good techniques to translate future precipitation patterns with the degree of resolution necessary to support the forecasting requirements necessary for road condition forecasting. Unfortunately, there is no definitive trend to develop such a program.

There is a movement to build MDC/AVL networks within many organizations to support MDSS and the monitoring of material use. It appears that these MDC/AVL programs will continue to increase with the ultimate goal that all vehicles in an Agency's fleet have units installed and operational. Communications should support the transfer of data from the field to the central processing center, thus making MDC/AVL an important tool for MDSS. One area in the MDC/AVL program that will need further emphasis is maintenance of the MDC/AVL units. To successfully support MDSS the installed units must remain a reliable resource. For MDSS an MDC/AVL unit that is not operational is akin to a truck that is not operational for use in maintenance.

6. RECOMMENDATIONS FOR FUTURE ROAD CONDITION REPORTING BEST PRACTICES

Road condition reporting appears to be a simple, straightforward process from an outside perspective. However, when the observation and reporting system is analyzed with the intent to automate the process, it becomes evident that it is a relatively complex set of steps and procedures. The most critical factor in the transition to an automated road condition reporting system is the observation of the state of the road and the weather conditions and the translation of the observation into a description that can be understood by an eventual user. The mental process used by an individual to select the appropriate road condition requires multiple separate input factors and often a synthesis of sequential observations over time. Section 2.5 presents the details associated with the each of the primary road condition class elements. The logic needed for an individual to determine the appropriate road condition class is what the automation process must emulate. A thorough analysis of the thought process suggests that the selection of a couple of the road condition classes actually represents the exclusion of other classifications (e.g., dry may actually result from the observer recognizing that no accumulation layer of any depth exists).

The analysis in this study addresses the potential use of mobile sensors or the output from MDSS as a mechanism to replace or augment the current visual observation and data communication process. The review indicates that there are substantial limitations with the existing mobile sensors and the MDSS techniques to support an automation process. However, there are evolving support techniques that offer ways to improve and possibly automate the current road condition observation and reporting process. The following recommendations represent the most reasonable options for future road condition reporting best practices.

RECOMMENDATION 1

IVR Entry of Road Conditions into an End-To-End Road Condition Reporting System

The existing system of road condition reporting remains the optimal technique to observe, report, organize, and disseminate road condition reports. The future system will integrate an IVR interface in maintenance vehicles that would accept verbal descriptions of the road conditions using a hands-free interface. An intelligent communications interface in the vehicle will store the road condition classes digitally and transmit the classification, time, and location descriptors upon verbal direction from the driver or system user. The intelligent communications interface will be logically connected via agency's communication network or a cellular network to the remainder of the road condition reporting system. Observations from field personnel will be processed and distributed to end users under the policies and practices set forth by the DOT.

Since it is likely that IVR technology will become a prevalent option within vehicles in the near future, it may be advantageous to view this recommended option as a backup system to any other recommended practice. Communications technologies have become robust solutions, and their acceptance will assure that providers resolve any issue with the systems very quickly.

RECOMMENDATION 2

Development of a Camera Network to Evaluate Road Conditions

The development of an image analysis module to assess road conditions from existing or an expanded network of cameras will provide a grid of road condition observations that are used to develop the current road condition along a segment of highway. The image analysis module will routinely assess the road condition within the field of view or multiple fields of view from a specific location and use the sequence of observations to ascertain the current road and weather conditions. The analyzed conditions generated by the image analysis module will collected at a central site and then integrated with the observations from other possible locations along a specified route to establish a final road condition analysis that meets the criteria of the responsible agency.

RECOMMENDATION 3

The Implementation of a Mobile Non-Contact Road Condition Sensor System

The best option for direct road condition analysis using mobile sensing devices is the use of a mobile package that can determine road condition using an integration of the following sensors: infrared non-contact road condition analyzer, infrared non-contact surface temperature sensor, and a temperature/RH sensor. The measurements made by these sensors will be used to logically evaluate the most probable state of the accumulation layer and transformed into the associated road condition class. The approach will need to go through extensive testing and possibly additional logic development to deal with the assessment of the appropriate road condition report that summarizes the variable conditions that exist along a section of highway. The future solution may need to integrate additional inputs to deal with road conditions that are outside of the measurement capability of the three described sensors, particularly for accumulation layer depths exceeding the sensor's depth measurement specifications.

Mobile non-contact sensors represent a new technology that offers great promise for automation of road condition reporting. To date, minimal testing has been done to demonstrate the level of performance of these sensors, and the limited set of reports raise some doubts regarding whether the current market options will meet the level of performance necessary to replace the current method of road condition reporting. The technique provides the mechanism to automate the assessment of road conditions, but it appears there is considerable verification and possible adjustments necessary before this approach is widely accepted as a best practice.

RECOMMENDATION 4

Other Techniques Toward Automation

Two other options exist that could be used to automate the observation of road conditions: a synthesis of multiple sensors, and road condition analysis and forecasting within MDSS. The analysis indicates that both of these approaches will require extensive development of either the sensing capability of particular sensors or the development of relatively dense networks of sensing equipment that has a high level of reliability and accuracy. Current trends in the industry and government organizations do not suggest that these objectives will be met in the near future; therefore, it is not envisioned that these techniques have the promise of becoming best practice approaches soon.

REFERENCES

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