Assessment of Montana Road Weather Information System

Benefit Cost Analysis

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1) INTRODUCTION

This interim report details the benefit cost analysis task as part of the overall project to assess the Montana Department of Transportation (MDT) Road Weather Information System (RWIS). This task determines the economic outcomes of different RWIS alternatives as defined in the prior task (*Weather Data and Software Analysis*). The alternatives defined in the prior task were also reviewed in consultation with the MDT project Technical Panel to ensure the most pertinent alternatives and approaches were included in this analysis.

The analysis includes the identified software functionalities in addition to different expansion scenarios. Specifically, alerting functionality, winter maintenance performance measures, and forecasting/MDSS functionalities were requested for investigation. Also requested was an analysis of different RWIS expansion alternatives (i.e. fixed stations compared to mobile RWIS, non-invasive sensors compared to in-pavement sensors). Table 1 shows the analysis alternatives, given that the expansion methods and software functionalities are not independent of one another.

Table 1: Analysis Alternatives

Coverage	Software Functionalities			
	Observational	Observational + Alerting	Observational + Forecast/MDSS	Observational + Perf. Measures
Current	Baseline	1	2	3 *
Current + Base Expansion	A	1 A	2 A	3 A *
Current + Simple Expansion	B	1 B	2 B	3 B *
Current + Non-Inv. Expansion	C	1 C	2 C	3 C *
Current + Mobile Expansion	D	1 D	2 D	3 D *

* Would require current coverage be supplemented with non-invasive sensors.
Note: Base expansion includes new ESS that are configured similarly to current base configuration.
Note: Simple expansion includes new ESS that have only a camera and in-pavement sensor.

In order to address the economic feasibility of both the software functionalities as well as the expansion alternatives, seven total scenarios (1, 2, 3, A, B, C, D) will need to be investigated in detail relative to the current baseline situation. The quantified details of these seven scenarios can then be used in combination to infill the remaining 12 possibilities (1A, 2A, etc.) which will

be a mix of the related benefits and costs while also accounting for any synergistic savings or benefits that may exist for certain combinations.

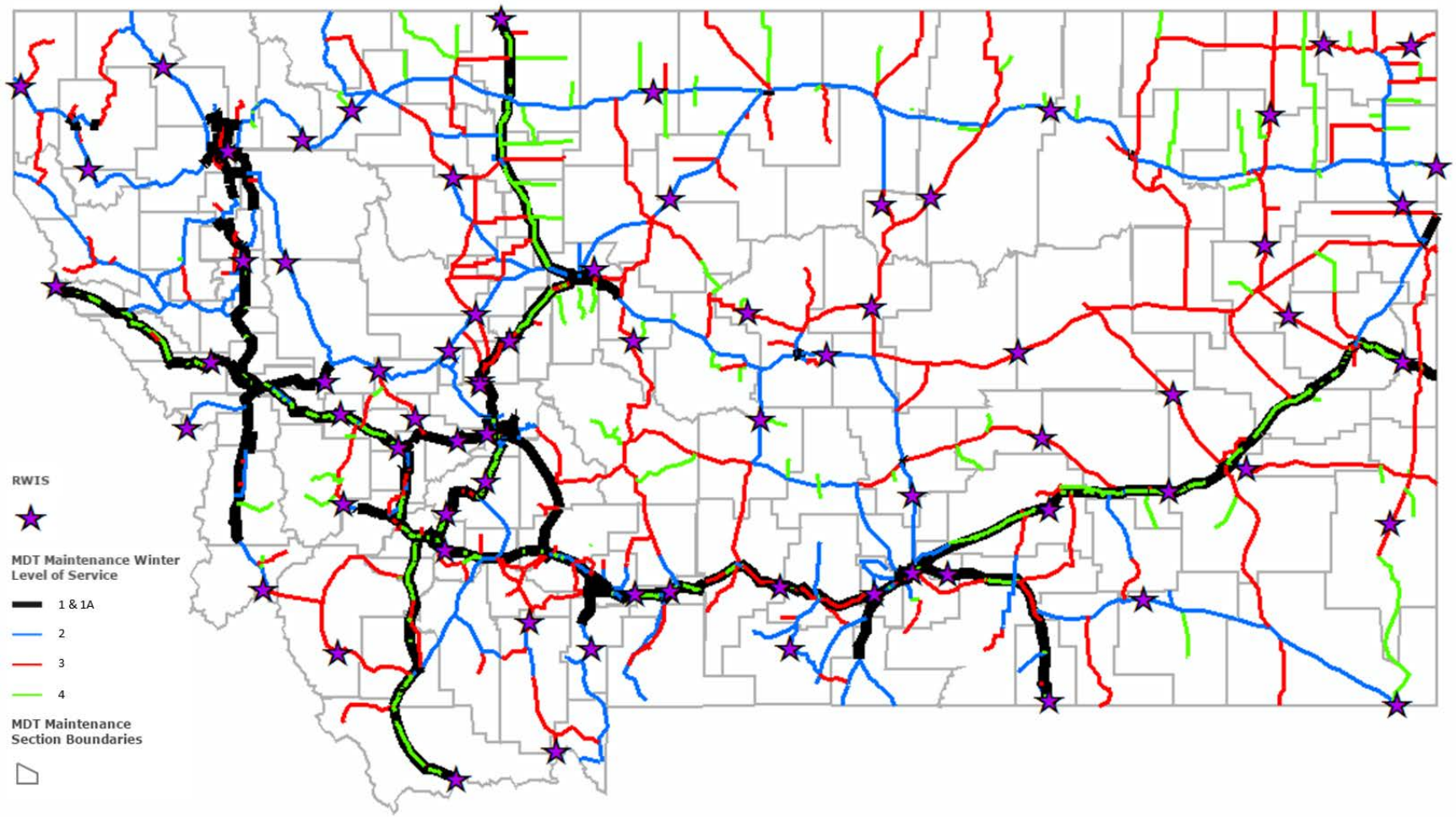
2) BACKGROUND

The current RWIS system is used by the primary users group, MDT winter maintenance personnel, to monitor conditions and make decisions related to preventing and removing ice and snow from Montana's roads. MDT maintenance personnel receive National Weather Service (NWS) forecasts and utilize other online, TV, and newspaper weather forecasts to be aware of upcoming winter storms. These forecasts help supervisors plan in advance of a storm in terms of how many crew members to have prepared and with what equipment and materials ready. Depending on the specifics of the storm forecast and the actual storm event, maintenance crews may utilize liquid or solid anti-icing or deicing materials, abrasives, pre-wetted abrasives, and snowplowing in various combinations. MDT practices "just-in-time" anti-icing, which is a practice that does not apply anti-icing materials until the actual start of a storm event (except for bridges and locations that receive little sunlight) in order to avoid applying anti-icing materials unnecessarily if a storm event doesn't materialize despite being forecast.

There are currently 118 maintenance sections around the state staffed by a total of approximately 709 winter maintenance crew members. Maintenance crews in each section maintain their roads according to certain Winter Maintenance Service Level Guidelines. These guidelines define levels of service and a general prioritization of winter maintenance activities and methods to be used depending on characteristics of each route. The different levels are:

- Type I & I-A: urban routes, Interstates, and other roads with ADT greater than 3000 vpd.
- Type II: roads with ADT from 1000 to 3000 vpd.
- Type III: roads with 200-1000 vpd.
- Type IV: roads with less than 200 vpd.
- Type V: roads that are seasonally closed and don't receive any regular winter maintenance treatments.

Each winter maintenance service level type includes specific guidelines for the typical methods and common treatment service hours to be expected. Figure 1 shows the different service levels, maintenance sections, and RWIS sites around the state.



*map does not show 7 satellite maintenance sections that operate within certain of the 118 sections (125 sections total)

Figure 1: Maintenance Sections, RWIS sites, and Winter Maintenance Service Levels

Some maintenance sections are tasked with maintaining mostly urban and Interstate routes while other maintenance sections primarily treat type III and IV roads. In general better RWIS coverage exists for those sections that are tasked with maintaining the higher service level roads.

The level of RWIS coverage may affect certain winter maintenance crew practices. For example, a crew in a remote section with poor RWIS coverage may need to rely on more patrolling to monitor the condition of roads and the potential start of a storm event, while a crew in a more urban area with good RWIS coverage may be able to largely avoid patrols and rely on RWIS observations. These differences affect the quantification of the benefits and costs associated with some of the alternatives in this economic analysis. As a result, and to provide the best possible estimates, the level of RWIS coverage was rated for each maintenance section on a 3 tier scale:

- Good RWIS coverage was assigned to a section if the majority of its roads are within 20 miles of RWIS sites.
- Fair RWIS coverage was assigned to a section if the majority of its roads are 20 to 40 miles from RWIS sites.
- Poor RWIS coverage was assigned to a section if the majority of its roads are more than 40 miles from RWIS sites.

These 3 general RWIS coverage classes will be used for benefit and cost calculations in the following sections. Overall 69 sections (58.5%) were found to have good RWIS coverage, 44 sections (37.3%) were found to have fair RWIS coverage, and 5 sections (4.2%) were found to have poor RWIS coverage.

Another quantity that affects many of the benefit cost scenarios is the level of geographic coverage related specifically to the different expansion methods. For calculation purposes a 25% geographic coverage expansion is used throughout the analyses. In accordance with coverage ranges from the literature reviewed in a prior task, a single RWIS site is assumed to have a geographic coverage of 25 miles. Actual RWIS coverage is highly dependent on local factors and is different for more mountainous western Montana geographies which may benefit from spacing even closer than 25 miles in certain instances compared to flatter eastern Montana areas that may be adequately covered with RWIS spacing greater than 25 miles.

3) BENEFITS AND COSTS OF ALTERNATIVES

Each alternative scenario is evaluated relative to the current baseline situation. Each scenario considers as many *documented/estimable* and *intangible/unquantified* benefits and costs as possible. In general this includes the following aspects:

Benefits

Agency

- Reduced maintenance labor or increased labor efficiency
- Reduced maintenance material use
- Reduced maintenance equipment use or increased equipment efficiency

Societal

- Reduced crash occurrence and/or severity
- Reduced travel time or reduced delays or improved LOS
- Better Traveler Information and related decision making

Costs

- Tower and foundation
- Sensors and hardware
- Communications
- Power
- Software
- Vendor services (e.g. forecasts, MDSS)
- Installation
- Training
- RWIS hardware and communications maintenance
- RWIS software operations & maintenance
- Administrative (e.g. management, protocol development)

While the best estimates available are used throughout this analysis, many individual costs and benefits have a limited amount of known data. The quantified benefits and costs are cited throughout this document to indicate their source be it existing literature, estimation, or vendor references. The values used reflect the researcher's best estimates, but readers are advised to exercise judgement in regards to the level of certainty associated with the assumptions required by the analyses. In general, benefit quantities are based on prior studies and conservative values are used. Vendor provided costs are typically rather rough estimates considering the uncertainty involved in changes to a large RWIS program. General estimates that apply to all scenarios are included in the following paragraphs with scenario specific values included in each respective scenario in subsections *3.1* through *3.20*.

The net present value of the benefits and costs for all scenarios are determined using a 10 year period and a 7% discount rate with all hardware having a 10 year life cycle. A range of benefit-cost ratios are established for each scenario using the agency specific benefits and total benefits (agency + societal) in comparison to a range of costs (minimum to maximum). The most and least costly software and sensor options are shown for each scenario in the following sections. Rough cost estimates are used as provided from RWIS vendors wherever possible.

MDT owned and operated software options are assumed to have similar yearly software maintenance costs as the current situation with MDT maintaining ScanWeb6. Fully hosted software options that may require no or little MDT software maintenance are assumed to have an approximate savings of ***$10,000*** per year. The purchasing of additional servers for MDT owned and maintained software are not included, and existing MDT hardware may or may not be adequate for some or all alternatives. In general the initial cost of hardware may be minimal compared to other costs over the life of the alternatives.

All software options, except for Vaisala products are assumed to have an initial migration and commissioning cost of ***$10,000*** related to initial set-up, polling and customization that may be required for non-Vaisala software integrating with existing Vaisala RPUs. Additional sensors required in expansionary scenarios are estimated to have ***$2,000*** to ***$4,000*** yearly hardware and communications maintenance costs (McKeever, et. al., 1998; Veneziano, et. al., 2014). Also new expansionary sensors are estimated to have ***$600*** per year power and communications costs.

The maximum benefit-cost ratio is determined using the lowest net present worth combination of software and hardware costs for each scenario noting that some more specialized sensors or functionalities may require same provider hardware-software combinations. Similarly, the minimum benefit-cost ratio is determined using the highest net present worth combination of software and hardware costs.

3.1. Baseline (Observational, No Expansion)

The current baseline scenario is described in the background section and all alternatives quantify benefits and costs relative to changes from the current baseline situation.

3.2. Scenario 1 (Observational + Alerting, No Expansion)

This scenario includes using the current RWIS sites with a software capable of providing customizable alerts for different weather conditions as well as for unresponsive or malfunctioning sensors and sites.

<u>Main Personnel Impacts</u>

- Maintenance crews could rely on an alert via email, text message, or phone call for specific RWIS weather conditions as opposed to needing to check RWIS sites periodically in anticipation of required winter maintenance activities. This would likely eliminate much the need to check RWIS observations in those sections with good and fair RWIS coverage.
- Alerts may also result in maintenance crews being able to optimally time activities, especially "just-in-time" anti-icing. The alerts would likely reduce the probability of starting activities later than desired by eliminating the potential for a crew member to miss or delay the checking of RWIS observations.
- Communications personnel could rely on alerts of problematic sensors and sites as opposed to being alerted by public users that may be using traveler information sources.

<u>Benefits</u>

Documented / Estimable:

- Reduced labor related to checking RWIS weather conditions.
    - 57.9 winter related event days per year (*documented: App. B*)
    - 11.6 maintenance sections effected per storm (*documented: App. B*)
    - 6 potentially effected personnel per section (*documented: App. B*)
    - $32 per hour average personnel rate with benefits (*provided*)
  - Sections with good RWIS coverage:
    - 10 minutes per effected crew member per storm event (*estimated*)
    - 69 sections with good RWIS coverage (*documented: Sec. 2*)
  - Sections with fair RWIS coverage:
    - 5 minutes per effected crew member per storm event (*estimated*)
    - 44 sections with fair RWIS coverage (*documented: Sec. 2*)

$$Savings = \left(\frac{10\ min}{60\ min/hr} * \frac{\$32}{crew,hr} * \frac{57.9\ stm}{yr} * \frac{11.6\ eff.sctns}{storm} * \frac{6\ crew}{eff.sctn} * \frac{69\ good\ sctns}{118\ total\ sctns}\right) + \left(\frac{5\ min}{60\ min/hr} * \frac{\$32}{crew,hr} * \frac{57.9\ stm}{yr} * \frac{11.6\ eff.sctns}{storm} * \frac{6\ crew}{eff.sctn} * \frac{44\ fair\ sctns}{118\ total\ sctns}\right) = \$\mathbf{16,575\ per\ yr}$$

- Reduced crash occurrence from less time with snowy/icy roads related to reduced late anti-icing, deicing and plowing.
    - 5% of storms with later-than-desired maintenance start (*estimated*)
    - $1.1665 crash cost savings per treated VMT (*documented: App. A*)
    - 30.92 MVMT storm effected traffic (*documented: App. B*)
  - Sections with good RWIS coverage:
    - 10 minutes less untreated road time per late-start storm event (*estimated*)
    - 69 sections with good RWIS coverage (*documented: Sec. 2*)
  - Sections with fair RWIS coverage:
    - 5 minutes less untreated road time per late-start storm event (*estimated*)

- 44 sections with fair RWIS coverage (*documented: Sec. 2*)

$$Savings = \left(5\% * \frac{10\ min}{storm} * \frac{1\ storm}{360\ min} * \frac{\$1.1665}{VMT} * \frac{30.92MVMT}{yr} * \frac{69\ good\ sctns}{118\ total\ sctns}\right) + \left(5\% * \frac{5\ min}{storm} * \frac{1\ storm}{360\ min} * \frac{\$1.1665}{VMT} * \frac{30.92MVMT}{yr} * \frac{44\ fair\ sctns}{118\ total\ sctns}\right) = \$\mathbf{38,632}\ per\ yr$$

- Reduced delay from less time with snowy/icy roads related to reduced late anti-icing, deicing and plowing.
  - 5% of storms with later-than-desired maintenance start (*estimated*)
  - $0.1469 delay cost savings per treated VMT (*documented: App. C*)
  - 30.92 MVMT storm effected traffic (*documented: App. B*)
  - Sections with good RWIS coverage:
    - 10 minutes less untreated road time per late-start storm event (*estimated*)
    - 69 sections with good RWIS coverage (*documented: Sec. 2*)
  - Sections with fair RWIS coverage:
    - 5 minutes less untreated road time per late-start storm event (*estimated*)
    - 44 sections with fair RWIS coverage (*documented: Sec. 2*)

$$Savings = \left(5\% * \frac{10\ min}{storm} * \frac{1\ storm}{360\ min} * \frac{\$1.1665}{VMT} * \frac{30.92MVMT}{yr} * \frac{69\ good\ sctns}{118\ total\ sctns}\right) + \left(5\% * \frac{5\ min}{storm} * \frac{1\ storm}{360\ min} * \frac{\$1.1665}{VMT} * \frac{30.92MVMT}{yr} * \frac{44\ fair\ sctns}{118\ total\ sctns}\right) = \$\mathbf{4,865}\ per\ yr$$

Intangible/Unquantified:

- Fewer reports from public of malfunctioning sites or sensors.
- Potentially less time with malfunctioning sites or sensors.

<u>Costs</u>

- Software
  - Minimum
    - Agency purchased and maintained software
      - ***$10,500*** purchase license (*vendors*)
      - ***-$0*** yearly O&M savings versus current (*see Sec. 3*)
      - ***$10,000*** initial migration (*see Sec. 3*)
  - Maximum
    - Hosted software service
      - ***$73,000*** per year (*vendors*)
      - ***-$10,000*** yearly O&M savings versus current (*see Sec. 3*)

Benefit - Cost Ratio

- Agency: ***0.3*** to ***5.7***
- Total: ***1.0*** to ***20.6***

3.3. Scenario 2 (Observational + Forecasting/MDSS, No Expansion)

This scenario includes using the current RWIS sites with a software and service capable of providing detailed atmospheric and pavement forecasts with some treatment recommendations type decision support based on the forecasts. Note that true "MDSS" treatment functionality is best obtained when an agency reports actual winter maintenance treatments back to the provider, which are then used to improve the forecasts and additional treatment recommendations (Ye, et. al., 2009b). The benefits of this scenario are based more on the value of improved weather forecasting information (that may or may not come with basic treatment recommendations), as opposed to full MDSS type benefits. Software options that provide forecasting and MDSS type information also typically have the alerting functionality as detailed in Scenario 1, so alerting functionality benefits are included where appropriate.

Main Personnel Impacts

- All impacts from Scenario 1.
- Improved atmospheric forecasting, pavement forecasting, and treatment recommendations have been shown to reduce total labor and material costs (Ye, et. al., 2009a; Strong & Shi, 2008; Shi, 2015).
- More precise forecasts with standardized treatment recommendations would likely increase the amount of proactive anti-icing performed overall. It will also likely allow for earlier treatments than the "just-in-time" anti-icing practices with more accurate and location specific forecasts resulting in fewer forecast storms that don't materialize.

Benefits

Documented / Estimable:

- Reduced labor from improved forecasting / decision support.
  - 11% (conservative) total labor cost reduction[1] (*Strong & Shi, 2008*)
  - $17.39M yearly winter maintenance labor costs (*documented: App. D*)

$$Savings = 11\% * \$17.39M = \$\mathbf{1.91M}\ per\ yr$$

[1] The labor savings related to alerting functionality is taken as part of the total 11% reduction and not included again.

- Reduced material use from improved forecasting / decision support.
    - 4% (conservative) total materials cost reduction (*Strong & Shi, 2008*)
    - $10.87M yearly winter maintenance materials costs (*documented: App. D*)
    -

$$Savings = 4\% * \$10.87M = \$\mathbf{434,800}\ per\ yr$$

- Reduced crash occurrence from less time with snowy/icy roads related to increased proactive anti-icing.
    - 10% more proactive anti-icing overall (*estimated*)
    - $0.1263 crash cost savings per treated VMT (*documented: App. A*)
    - 30.92 MVMT storm effected traffic (*documented: App. B*)

$$Savings = 10\% * \frac{\$0.1263}{VMT} * 30.92MVMT = \$\mathbf{390,520}\ per\ yr$$

- Reduced delay from less time with snowy/icy roads related to increased proactive anti-icing.
    - 10% more proactive anti-icing overall (*estimated*)
    - $0.0294 delay cost savings per treated VMT (*documented: App. C*)
    - 30.92 MVMT storm effected traffic (*documented: App. B*)

$$Savings = 10\% * \frac{\$0.0294}{VMT} * 30.92MVMT = \$\mathbf{90,905}\ per\ yr$$

Intangible/Unquantified:

- Ability to have consistent statewide treatment suggestion protocols based on conditions and forecasts.
- Fewer reports from public of malfunctioning sites or sensors.
- Potentially less time with malfunctioning sites or sensors.

<u>Costs</u>

- Software
    - Minimum
        - Agency purchased and vendor maintained software
            - ***$417,600*** purchase license (*vendors*)
            - ***$20,100*** yearly vendor maintenance (*vendors*)
            - ***-$10,000*** yearly O&M savings versus current (*see Sec. 3*)
            - ***$10,000*** initial migration (*see Sec. 3*)
    - Maximum
        - Hosted software service
            - ***$146,300*** per year (*vendors*)
            - ***-$10,000*** yearly O&M savings versus current (*see Sec. 3*)

- ***$10,000*** initial migration (*see Sec. 3*)

Benefit - Cost Ratio

- Agency: ***17.1*** to ***29.8***
- Total: ***20.5*** to ***36.0***

3.4. Scenario 3 (Observational + Performance Measures, No Expansion)

This scenario includes using the current RWIS sites with a software and service capable of providing automated performance measures information. Automated performance measures require the use of non-invasive sensor technologies capable of estimating a grip level. This scenario will consider equipping 25% of the current sites with non-invasive sensors which will result in approximately 25% of the storm effected VMT being influenced (a conservative estimate as it is more likely non-invasive sensors would be placed at winter maintenance service level I and IA routes that serve higher traffic levels). Software that provides automated performance measures also provides alerting functionality, so those impacts are included where appropriate. The software that provides automated performance measures also has an option to also provide forecasting and MDSS type information. Benefit-cost ratios are therefore provided with and without the advanced forecasting/MDSS options.

Main Personnel Impacts

- All impacts from Scenarios 1[2] and 2.
- The use of automated performance measures is only known to have been implemented in one state transportation agency (Idaho). That agency has reported improvements in overall winter road conditions related to their ability to adjust winter maintenance activities based on monitoring the grip levels of the roadway (Koeberlein, et. al., 2014; Koeberlein, 2015).

Benefits

Documented / Estimable:

- Reduced material use from grip monitoring and material use optimization.
  - Only for sections with non-invasive sensor coverage:
    - 25% of total VMT with non-invasive coverage (*assumed above*)
    - 20% (conservative) total materials cost reduction (*documented: App. E*)
    - $10.87M yearly winter maintenance materials costs (*documented: App. D*)

$$Savings = 25\% * 20\% * \$10.87M = \$\mathbf{543,500}\ per\ yr$$

[2] In the case of not having forecasts, labor saving from alerting functionality is included.

- Reduced crash occurrence from less time with lower grip levels.
  - Only for sections with non-invasive sensor coverage:
    - 25% of total VMT with non-invasive coverage (*assumed above*)
    - $0.2101 crash cost savings per treated VMT (*documented: App. E*)
    - 30.92 MVMT storm effected traffic (*documented: App. B*)

$$Savings = 25\% * \frac{\$0.2101}{VMT} * 30.92MVMT = \$\mathbf{1.62M}\ per\ yr$$ [3]

- Reduced delay from less time with lower grip levels.
  - Only for sections with non-invasive sensor coverage:
    - 25% of total VMT with non-invasive coverage (*assumed above*)
    - $0.0499 crash cost savings per treated VMT (*documented: App. E*)
    - 30.92 MVMT storm effected traffic (*documented: App. B*)

$$Savings = 25\% * \frac{\$0.0499}{VMT} * 30.92MVMT = \$\mathbf{385,727}\ per\ yr$$

Intangible/Unquantified:

- Ability to monitor and report winter maintenance performance measures in terms of improved mobility and safety provided to the travelling public.
- Ability to have consistent statewide treatment suggestion protocols based on conditions and forecasts if advanced forecasting is used.
- Fewer reports from public of malfunctioning sites or sensors.
- Potentially less time with malfunctioning sites or sensors.

<u>Costs</u>

- Software
  - One option
    - Hosted software service (without forecasting)
      - ***$76,650*** per year (*vendors*)
      - ***-$10,000*** yearly O&M savings versus current (*see Sec. 3*)
    - Hosted software service (with forecasting)
      - ***$89,800*** per year (*vendors*)
      - ***-$10,000*** yearly O&M savings versus current (*see Sec. 3*)

[3] Conservative compared to crash reductions observed with similar sensor numbers in Idaho (Koeberlein, et. al., 2014).

- Hardware
    - Noninvasive Sensors (matching single option software)
        - ***$20,000*** each (*vendors*)

Benefit - Cost Ratio

- Agency (without forecasting): ***~4.8***
- Total (without forecasting): ***~21.8***

- Agency (with forecasting): ***~17.9***
- Total (with forecasting): ***~33.3***

3.5. Scenario A (Observational, Base Expansion)

This scenario includes using the current observational software with the current RWIS sites and 18 additional "base" RWIS sites which are configured to include the same equipment as the majority of the current sites.

Main Personnel Impacts

- Maintenance crews in expansion areas that currently have poor or fair RWIS coverage would likely be improved to good RWIS coverage and could then reduce patrolling by relying on RWIS observations.

Benefits

Documented / Estimable:

- Reduced labor and equipment use related to fewer patrols.
    - 57.9 winter related event days per year (*documented: App. B*)
    - 11.6 maintenance sections effected per storm (*documented: App. B*)
    - 6 potentially effected personnel per section (*documented: App. B*)
    - $32 per hour average personnel rate with benefits (*provided*)
    - $30 per hour patrol vehicle cost (*estimated*)
  - Sections with previously poor RWIS coverage:
    - 30 minutes per effected crew member per storm event (*estimated*)
    - 5 improved coverage sections (*documented: Sec. 2*)
  - Sections with previously fair RWIS coverage:
    - 15 minutes per effected crew member per storm event (*estimated*)
    - 13 improved coverage sections (*documented: Sec. 2*)

$$Savings = \left(\frac{30\ min}{60\ min/hr} * \frac{\$62}{crew,hr} * \frac{57.9\ stm}{yr} * \frac{11.6\ eff.sctns}{storm} * \frac{6\ crew}{eff.sctn} * \frac{5\ sctns}{118\ total\ sctns}\right) + \left(\frac{15\ min}{60\ min/hr} * \frac{\$62}{crew,hr} * \frac{57.9\ stm}{yr} * \frac{11.6\ eff.sctns}{storm} * \frac{6\ crew}{eff.sctn} * \frac{13\ fair\ sctns}{118\ total\ sctns}\right) = \$\mathbf{12,175}\ \boldsymbol{per\ yr}$$

- Reduced crash occurrence from improved conditions due to RWIS presence improvements.
    - 30.92 MVMT storm effected traffic (*documented: App. B*)
  - Sections with previously poor RWIS coverage:
    - $0.0618 crash cost savings per treated VMT (*documented: App. A*)
    - 5 improved coverage sections (*documented: Sec. 2*)
  - Sections with previously fair RWIS coverage:
    - $0.0309 crash cost savings per treated VMT (*documented: App. A*)
    - 13 improved coverage sections (*documented: Sec. 2*)

$$Savings = \left(\frac{5\ sctns}{118\ total\ sctns} * \frac{\$0.0618}{VMT} * 30.92MVMT\right) + \left(\frac{13\ sctns}{118\ total\ sctns} * \frac{\$0.0309}{VMT} * 30.92MVMT\right) = \$\mathbf{186,227}\ per\ yr$$

- Reduced delay from improved conditions due to RWIS presence.
    - 30.92 MVMT storm effected traffic (*documented: App. B*)
  - Sections with previously poor RWIS coverage:
    - $0.0147 crash cost savings per treated VMT (*documented: App. C*)
    - 5 improved coverage sections (*documented: Sec. 2*)
  - Sections with previously fair RWIS coverage:
    - $0.00735 crash cost savings per treated VMT (*documented: App. C*)
    - 13 improved coverage sections (*documented: Sec. 2*)

$$Savings = \left(\frac{5\ sctns}{118\ total\ sctns} * \frac{\$0.0147}{VMT} * 30.92MVMT\right) + \left(\frac{13\ sctns}{118\ total\ sctns} * \frac{\$0.00735}{VMT} * 30.92MVMT\right) = \$\mathbf{44,297}\ per\ yr$$

Intangible/Unquantified:

- Improved Traveler Information in areas that may have had no information.
- Improved information, especially camera images, for MDT Aeronautics and general aviation.
- Certain in-pavement sensors can output a friction estimate allowing for the possibility to store and review basic mobile sensor grip level information.

<u>Costs</u>

- Hardware
    - ***$35,000*** to ***$45,000*** per new base site (*estimate*)

- ***$2,000*** to ***$4,000*** yearly hardware and communications maintenance per site (*see Sec. 3*)
- ***$600*** yearly power and communications costs per site (*see Sec. 3*)

Benefit - Cost Ratio

- Agency: ***0.06*** to ***0.09***
- Total: ***1.2*** to ***1.8***

3.6. Scenario B (Observational, Simple Expansion)

This scenario includes using the current observational software with the current RWIS sites and 18 additional "simple" RWIS sites which are configured to include only a camera and pavement temperature sensor.

Main Personnel Impacts

- Same as Scenario A

Benefits

Documented / Estimable:

- Reduced labor and equipment use related to fewer patrols (from Scenario A).
  - ***$12,175*** per year in labor and equipment savings (*calculated*)
- Reduced crashes from improved conditions due to RWIS presence (from Scenario A).
  - ***$186,227*** per year in crash cost savings (*calculated*)
- Reduced delay from improved conditions due to RWIS presence (from Scenario A).
  - ***$44,297*** per year in delay cost savings (*calculated*)

Intangible/Unquantified:

- Improved Traveler Information in areas that may have had no information.
- Improved information, especially camera images, for MDT Aeronautics and general aviation.

Costs

- Hardware
  - ***$8,000*** to ***$12,000*** per new simple site (*estimate*)
  - ***$2,000*** to ***$4,000*** yearly hardware and communications maintenance per site (*see Sec. 3*)
  - ***$600*** yearly power and communications costs per site (*see Sec. 3*)

Benefit - Cost Ratio

- Agency: ***0.11*** to ***0.18***

- Total: ***2.1*** to ***3.6***

3.7. Scenario C (Observational, Non-Invasive Expansion)

This scenario includes using the current observational software with the current RWIS sites and 18 additional RWIS sites that use non-invasive sensors instead of in-pavement sensors.

Main Personnel Impacts

- Same as Scenario A

Benefits

Documented / Estimable:

- Reduced labor and equipment use related to fewer patrols (from Scenario A).
    - ***$12,175*** per year in labor and equipment savings (*calculated*)
- Reduced crashes from improved conditions due to RWIS presence (from Scenario A).
    - ***$186,227*** per year in crash cost savings (*calculated*)
- Reduced delay from improved conditions due to RWIS presence (from Scenario A).
    - ***$44,297*** per year in delay cost savings (*calculated*)

Intangible/Unquantified:

- Possibility to store and review grip recovery type performance measures information for the 18 non-invasive sites.
- Improved Traveler Information in areas that may have had no information.
- Improved information, especially camera images, for MDT Aeronautics and general aviation.

Costs

- Hardware
    - ***$50,000*** to ***$60,000*** per new non-invasive site (*estimate*)
    - ***$2,000*** to ***$4,000*** yearly hardware and communications maintenance per site (*see Sec. 3*)
    - ***$600*** yearly power and communications costs per site (*see Sec. 3*)

Benefit - Cost Ratio

- Agency: ***0.05*** to ***0.07***
- Total: ***1.0*** to ***1.4***

3.8. Scenario D (Observational, Mobile Expansion)

This scenario includes using the current RWIS sites and 12 additional mobile RWIS sites[4]. Since the current software does not support mobile RWIS sensors, this scenario also includes obtaining a software product that supports mobile RWIS sensors. This scenario includes using mobile RWIS on maintenance vehicles during typical winter maintenance activities and not creating trips solely for mobile RWIS weather observation. Benefits in this and other "D" scenarios are limited by a lack of quantified information in the literature. Mobile RWIS coverage is fundamentally different from fixed site RWIS coverage, mainly due to the temporal availability of mobile RWIS observations being centered around storm response activities. This benefit model may be somewhat optimistic regarding the overall benefits of mobile RWIS as it quantifies only coverage related to winter maintenance activities and does not include any quantification of non-winter maintenance RWIS uses that may be better served by fixed sites.

Main Personnel Impacts

- Maintenance crews would have real-time conditions monitoring on any routes traveled by the 12 vehicles equipped with the mobile sensors.

Benefits

Documented / Estimable:

- Reduced labor and equipment use related to fewer patrols (from Scenario A).
    - Little to no patrolling savings would be realized from mobile sensor use as data is only gathered during maintenance vehicle travel.
    - ***$0*** per year in labor and equipment use savings (*estimated*)
- Reduced crashes from improved conditions due to RWIS presence (from Scenario A).
    - Depending on their geographical use areas, 12 mobile sensors would have similar coverage as 18 fixed sites, therefore similar coverage related benefits are used here.
    - ***$186,227*** per year in crash cost savings (*calculated*)
- Reduced delay from improved conditions due to RWIS presence (from Scenario A).
    - Depending on their geographical use areas, 12 mobile sensors would have similar coverage as 18 fixed sites, therefore similar coverage related benefits are used here.
    - ***$44,297*** per year in delay cost savings (*calculated*)

[4] Mobile RWIS estimated to have 1.5 times the geographic coverage of a fixed RWIS based on 25 mile coverage radius and 50 mph travel speed (see Appendix F). Therefore the 25% geographic expansion is 18 fixed RWIS or 12 mobile RWIS.

Intangible/Unquantified:

- Improved Traveler Information (similar to MDT snow plow cameras pilot project), but only during winter storm patrolling sensor use.
- Possibility to store and review basic mobile sensor grip level information.

Costs

- Software
  - Minimum
    - Hosted software service
      - ***$42,500*** per year (*vendors*)
      - ***-$10,000*** yearly O&M savings versus current (*see Sec. 3*)
      - ***$10,000*** initial migration (*see Sec. 3*)
  - Maximum
    - Hosted software service
      - ***$89,250*** per year (*vendors*)
      - ***-$10,000*** yearly O&M savings versus current (*see Sec. 3*)

- Hardware
  - ***$8,000*** to ***$18,500*** per new mobile sensor (*vendors*)
  - ***$2,000*** to ***$4,000*** yearly hardware and communications maintenance per site (*see Sec. 3*)
  - ***$600*** yearly power and communications costs per site (*see Sec. 3*)

Benefit - Cost Ratio

- Agency: ***No quantified agency specific benefits***
- Total: ***1.4*** to ***2.9***

3.9. Scenario 1-A (Observational + Alerting, Base Expansion)

This scenario includes using the base expansion sites with an alerting capable software.

Main Personnel Impacts, Benefits, and Costs

All personnel impacts, benefits and costs are the same as those included in Scenarios 1 & A except:

- The maximum software cost is increased to a hosted yearly cost of ***$91,000*** (*vendors*)

Benefit - Cost Ratio

- Agency: ***0.1*** to ***0.2***
- Total: ***1.1*** to ***2.2***

3.10. Scenario 1-B (Observational + Alerting, Simple Expansion)

This scenario includes using the simple expansion sites with an alerting capable software.

Main Personnel Impacts, Benefits, and Costs

All personnel impacts, benefits and costs are the same as those included in Scenarios 1 & B except:

- The maximum software cost is increased to a hosted yearly cost of ***$91,000*** (*vendors*)

Benefit - Cost Ratio

- Agency: ***0.2*** to ***0.4***
- Total: ***1.6*** to ***4.3***

3.11. Scenario 1-C (Observational + Alerting, Non-Invasive Expansion)

This scenario includes using the non-invasive expansion sites with an alerting capable software.

Main Personnel Impacts, Benefits, and Costs

All personnel impacts, benefits and costs are the same as those included in Scenarios 1 & C except:

- The maximum software cost is increased to a hosted yearly cost of ***$91,000*** (*vendors*)

Benefit - Cost Ratio

- Agency: ***0.1*** to ***0.2***
- Total: ***1.0*** to ***1.7***

3.12. Scenario 1-D (Observational + Alerting, Mobile Expansion)

This scenario includes using the mobile expansion sites with an alerting capable software. Mobile RWIS monitoring software is also required.

Main Personnel Impacts, Benefits, and Costs

All personnel impacts, benefits and costs are the same as those included in Scenarios 1 & D.

Benefit - Cost Ratio

- Agency: ***0.1*** to ***0.2***
- Total: ***1.8*** to ***3.7***

3.13. Scenario 2-A (Observational + Forecasting/MDSS, Base Expansion)

This scenario includes using the base expansion sites with software that includes advanced forecasting and treatment suggestion type information. Software options that provide forecasting and MDSS type information also typically have alerting functionality.

Main Personnel Impacts, Benefits, and Costs

All personnel impacts, benefits and costs are the same as those included in Scenarios 2 & A except:

- The minimum software cost is increased to an agency purchased software license of ***$532,000*** with a yearly vendor maintenance fee of ***$23,000*** per year (*vendors*)

Benefit - Cost Ratio

- Agency: ***5.7*** to ***8.5***
- Total: ***7.9*** to ***11.6***

3.14. Scenario 2-B (Observational + Forecasting/MDSS, Simple Expansion)

This scenario includes using the simple expansion sites with software that includes advanced forecasting and treatment suggestion type information. Software options that provide forecasting and MDSS type information also typically have alerting functionality.

Main Personnel Impacts, Benefits, and Costs

All personnel impacts, benefits and costs are the same as those included in Scenarios 2 & B except:

- The minimum software cost is increased to an agency purchased software license of ***$532,000*** with a yearly vendor maintenance fee of ***$23,000*** per year (*vendors*)
- The maximum software cost is increased to a hosted yearly cost of ***$173,800*** (*vendors*)

Benefit - Cost Ratio

- Agency: ***6.9*** to ***12.2***
- Total: ***9.5*** to ***16.8***

3.15. Scenario 2-C (Observational + Forecasting/MDSS, Non-Invasive Expansion)

This scenario includes using the non-invasive expansion sites with software that includes advanced forecasting and treatment suggestion type information. Software options that provide forecasting and MDSS type information also typically have alerting functionality.

Main Personnel Impacts, Benefits, and Costs

All personnel impacts, benefits and costs are the same as those included in Scenarios 2 & C except:

- The minimum software cost is increased to an agency purchased software license of ***$532,000*** with a yearly vendor maintenance fee of ***$23,000*** per year (*vendors*)
- The maximum software cost is increased to a hosted yearly cost of ***$173,800*** (*vendors*)

Benefit - Cost Ratio

- Agency: ***4.8*** to ***7.3***
- Total: ***6.6*** to ***10.0***

3.16. Scenario 2-D (Observational + Forecasting/MDSS, Mobile Expansion)

This scenario includes using the mobile expansion sites with software that includes advanced forecasting and treatment suggestion type information. Software options for this scenario also include mobile RWIS support. Mobile RWIS, especially when coupled with Mobile Data Collection (MDC) / Automatic Vehicle Location (AVL) technologies, may achieve substantial MDSS type benefits related to automated treatment feedback and improved forecasting, but that type of implementation is not included in this scenario as AVL was not desired as an alternative direction to investigate during consultation with the technical panel (Chien, et. al., 2014).

Main Personnel Impacts, Benefits, and Costs

All personnel impacts, benefits and costs are the same as those included in Scenarios 2 & D except:

- The software cost changes to a single option hosted yearly cost of ***$104,600*** (*vendors*)
- The minimum hardware cost changes to a single option of ***$18,500*** each (*vendors*)

Benefit - Cost Ratio

- Agency: ***~ 10.5***
- Total: ***~ 14.5***

3.17. Scenario 3-A (Observational + Performance Measures, Base Expansion)

This scenario includes using the base expansion sites with a software and service capable of providing automated performance measures information. Like Scenario 3 this case considers a 25% retrofit of non-invasive sensors at existing sites.

Main Personnel Impacts, Benefits, and Costs

All personnel impacts, benefits and costs are the same as those included in Scenarios 3 & A except:

- The software costs increase to ***$95,600*** per year (without forecasting) and ***$111,900*** per year (with forecasting) (*vendors*)

Benefit - Cost Ratio

- Agency (without forecasting): ***1.7*** to ***2.1***
- Total (without forecasting): ***8.4*** to ***10.3***

- Agency (with forecasting): ***6.7*** to ***8.2***
- Total (with forecasting): ***13.1*** to ***15.9***

3.18. Scenario 3-B (Observational + Performance Measures, Simple Expansion)

This scenario includes using the simple expansion sites with a software and service capable of providing automated performance measures information. Like Scenario 3 this case considers a 25% retrofit of non-invasive sensors at existing sites.

Main Personnel Impacts, Benefits, and Costs

All personnel impacts, benefits and costs are the same as those included in Scenarios 3 & B except:

- The software costs increase to ***$95,600*** per year (without forecasting) and ***$111,900*** per year (with forecasting) (*vendors*)

Benefit - Cost Ratio

- Agency (without forecasting): ***2.3*** to ***2.8***
- Total (without forecasting): ***11.2*** to ***13.8***

- Agency (with forecasting): ***8.9*** to ***10.7***
- Total (with forecasting): ***17.3*** to ***20.9***

3.19. Scenario 3-C (Observational + Performance Measures, Non-Invasive Expansion)

This scenario includes using the non-invasive expansion sites with a software and service capable of providing automated performance measures information. Like Scenario 3 this case considers a 25% retrofit of non-invasive sensors at existing sites.

Main Personnel Impacts, Benefits, and Costs

All personnel impacts, benefits and costs are the same as those included in Scenarios 3 & C except:

- The software costs increase to ***$95,600*** per year (without forecasting) and ***$111,900*** per year (with forecasting) (*vendors*)
- The non-invasive sensors in the expansion will increase the amount of the network that can benefit from the automated performance measures functionality.

Benefit - Cost Ratio

- Agency (without forecasting): ***3.7*** to ***4.5***
- Total (without forecasting): ***15.1*** to ***18.1***

- Agency (with forecasting): ***6.1*** to ***7.2***
- Total (with forecasting): ***17.0*** to ***20.2***

3.20. Scenario 3-D (Observational + Performance Measures, Mobile Expansion)

This scenario includes using the mobile expansion sites with a software and service capable of providing automated performance measures information. Like Scenario 3 this case considers a 25% retrofit of non-invasive sensors at existing sites.

Main Personnel Impacts, Benefits, and Costs

All personnel impacts, benefits and costs are the same as those included in Scenarios 3 & B except:

- The software costs increase to ***$89,300*** per year (without forecasting) and ***$104,600*** per year (with forecasting) (*vendors*)
- While mobile RWIS sensors can provide grip readings similarly to the non-invasive sensors, the automated performance measures currently available require wind sensors inputs which are not easily obtained on a moving vehicle. The automated performance measures also require reading at the same point over time to track changes and this may or may not be feasible depending on individual mobile sensor routes and travel times. The mobile RWIS included in this scenario therefore do not contribute to an increase in the amount of the network that can benefit from the automated performance measures functionality. Modified performance measures or in-house agency monitoring of basic grip information may be beneficial, but that is not quantified in this scenario.

Benefit - Cost Ratio

- Agency (without forecasting): ***~ 3.2***
- Total (without forecasting): ***~ 12.7***

- Agency (with forecasting): ***~ 10.1***
- Total (with forecasting): ***~ 19.7***

4) SUMMARY

Many of the scenarios investigated show the promise of favorable benefit-cost ratios using the information and assumptions included in the analysis. All agency specific benefit-cost ratio ranges are shown in Table 2.

Table 2: Agency Specific Benefit-Cost Ratios

AGENCY	Current Software		1 (+Alerting)		2 (+F.cast)		3 (+P.M.) no F.cast		3 (+P.M.) with F.cast	
	min	max	min	max	min	max	min	max	min	max
Current Sites	Baseline		0.3	5.7	17.1	29.8	~ 4.8		~ 17.9	
A (+Base)	0.06	0.09	0.1	0.2	5.7	8.5	1.7	2.1	6.7	8.1
B (+Simple)	0.11	0.18	0.2	0.4	6.9	12.2	2.3	2.8	8.9	10.7
C (+N-I)	0.05	0.07	0.1	0.2	4.8	7.3	3.7	4.5	6.1	7.2
D (+Mob.)	NA		0.1	0.2	~ 10.5		~ 3.2		~ 10.1	

Agency specific benefits tend to outweigh the costs for all scenarios that utilize the current sensor locations when adding new functionalities. Advanced forecasting functionality may produce the highest agency savings, and alerting and automated performance measures functionalities may produce somewhat smaller, but still significant agency savings. All methods of RWIS coverage expansion tend to reduce the agency benefit-cost ratios somewhat when compared to using the current sites with improved functionalities alone.

When societal benefits are considered along with agency savings the benefit-cost ratios increase for all scenarios as shown in Table 3.

Table 3: Total (Agency + Societal) Benefit-Cost Ratios

TOTAL	Current Software		1 (+Alerting)		2 (+F.cast)		3 (+P.M.) no F.cast		3 (+P.M.) with F.cast	
	min	max	min	max	min	max	min	max	min	max
Current Sites	Baseline		1.0	20.6	20.5	36.0	~ 21.8		~ 33.3	
A (+Base)	1.2	1.8	1.1	2.2	7.9	11.6	8.4	10.3	13.1	15.9
B (+Simple)	2.1	3.6	1.6	4.3	9.5	16.8	11.2	13.8	17.3	20.1
C (+N-I)	1.0	1.4	1.0	1.7	6.6	10.0	15.1	18.1	17.0	20.2
D (+Mob.)	1.4	2.9	1.8	3.7	~ 14.5		~ 12.7		~ 19.7	

In general the most promising scenarios considering all benefits are:

- obtaining alerting functionality with no site expansion,
- obtaining automated performance measures, which require at least some current sites adding non-invasive sensors, and possibly expanding with new non-invasive sites,
- obtaining advanced forecasting functionality using the current sites, or
- obtaining both automated performance measures and advanced forecasting using the existing sites (with required non-invasive sensors) or the simple expansion sites or the non-invasive expansion sites, or the mobile expansion sites.

While certain scenarios reflect high benefit-cost ratios, their cost to implement will also be a factor in deciding what ultimately may be deployed. The minimum estimated first year and recurring costs are shown in Table 4. These values reflect the options with the minimum total present value over the total ten year analysis period.

Table 4: Minimum Estimated Costs ($ thousands, rounded to nearest thousand)

TOTAL	Current Software		1 (+Alerting)		2 (+F.cast)		3 (+P.M.) no F.cast		3 (+P.M.) with F.cast	
	1st yr	recur.	1st yr	recur.	1st yr	recur.	1st yr	recur.	1st yr	recur.
Current Sites	Baseline		21	0	492*	10*	427	67	440	80
A (+Base)	677	47	697	47	1,232	60	1,122	132	1,139	149
B (+Simple)	191	47	211	47	746	60	636	132	653	149
C (+N-I)	947	47	967	47	1,502	60	1,392	132	1,409	149
D (+Mob.)	170	64	170	31	222	31	567	111	582	126

* Fully hosted options are available with lower 1st year costs, but higher overall costs over ten year analysis period.

Most scenarios with the highest total benefit-cost ratios are also the most costly and may or may not be feasible with current MDT funding availability. Specifically, some of the most promising scenarios may require significant investments of hundreds of thousands of dollars above current RWIS funding amounts. One scenario, obtaining alerting functionality without expanding sites, is potentially both relatively low cost and highly beneficial, depending on the specific software product used.

These benefit-cost results and overall scenario costs will be considered together with the findings from the previous tasks in developing the RWIS implementation plan in the following task.

5) REFERENCES

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6) APPENDIX A: CRASH REDUCTIONS

Table 5 shows the crash costs for different crash types as defined by the American Association of State Highway and Transportation Officials (AASHTO) in the Highway Safety Manual (HSM). Costs are adjusted to represent 2016 dollars using US Bureau of Labor Statistics Consumer Price Index and Employment Cost Index methods as suggested in the HSM.

Table 5: Crash Costs (rounded to nearest thousand)

Crash Type	HSM Cost
PDO	$10,000
Injury C	$62,000
Injury B	$111,000
Injury A	$303,000
Fatal	$5,712,000

Using methods from McKeever et al. (1998) with updated crash costs, RWIS presence results in approximately ***10%*** more time with road conditions wet as opposed to icy/snowy during storm events. This results in a crash reduction savings of ***$0.0618*** per VMT. This saving rate can then be used with a storm effected VMT amount to find crash dollars saved for adding RWIS where none was previously present. Half of this rate will be used for "fair" to "good" RWIS coverage improvements.

Using methods from McKeever et al. (1998) with updated crash costs and findings from another study (Blackburn et al., 1994[5]), proactive anti-icing compared to conventional deicing results in approximately ***20%*** more time with road conditions wet as opposed to icy/snowy during storm events. This results in a crash reduction savings of ***$0.1236*** per VMT. This saving rate can then be used with a storm effected VMT amount to find crash dollars saved.

Using methods from another study (Hanbali, 1994[6]), winter maintenance activities compared to performing no winter maintenance activities results in an approximate crash reduction savings of ***$1.1665*** per VMT. This saving rate can then be used with a storm effected VMT amount to find crash dollars saved.

[5] Blackburn, R., McGrane, E., Chappelow, C., and Harwood, D. "Development of Anti-Icing Technology." Strategic Highway Safety Program Report SHRP-H-385. 1994.
[6] Hanbali, R. "Economic Impact of Winter Road Maintenance on Road Users." *Transportation Research Record: Journal of the Transportation Research Board*. No 1442. 1994.

7) APPENDIX B: STORM EVENTS AND EFFECTED CREW

Storm Effected VMT:

Using only state owned roads and most recently available data, Montana experiences approximately ***9,496*** MVMT per year[7].

Using NOAA database records over the past ten available winter seasons (2005-2006 through 2014-2015), Montana has experienced an average of ***57.9*** days per year with a winter related storm event be it a blizzard, freezing fog, heavy snow, ice storm, winter storm, or winter weather[8]. To be conservative it is assumed that each storm day corresponds to a single event per day. These winter events effect an average of ***5.5*** counties per event-day, which is equivalent to approximately ***11.6*** maintenance sections affected per event-day.

Assuming an average winter related storm event lasts ***6*** hours, the average yearly winter storm effected VMT is then approximately 37.02 MVMT for the state. Further adjusting this VMT for the fact that traffic levels in the winter months (October through March) are lower than the yearly average traffic[9] yields an adjusted yearly winter storm effected VMT is then approximately ***30.92*** MVMT for the state.

There are total winter 709 maintenance crew in 118 maintenance sections which results in approximately ***6*** potentially effected winter maintenance crew per storm effected maintenance section.

[7] Traffic Data. Montana Department of Transportation. http://www.mdt.mt.gov/publications/datastats/traffic_maps.shtml accessed April 25, 2016.
[8] Storm Events Database. NOAA - National Centers for Environmental Information. http://www.ncdc.noaa.gov/stormevents/ accessed April 25, 2016.
[9] Montana's Estimated Monthly Vehicle Miles Traveled. MDT. http://www.mdt.mt.gov/other/webdata/external/Planning/traffic_reports/mvmt_table.pdf Accessed May 31, 2016.

8) APPENDIX C: TRAVEL DELAY REDUCTIONS

The average speed reduction for arterials is approximately ***35%*** for snowy or slushy pavement[10].

The cost of time for a passenger car with 1.25 average occupancy is ***$22.09*** per hour and cost of time for commercial vehicle is ***$94.04*** per hour[11].

Assuming passenger cars have an overall average speed of 70 mph in normal conditions and commercial vehicles have an average overall speed of 60 mph in normal conditions and using an average of 25% speed reduction (35% for snow - 10% for wet) leads to delay costs for snowy roads compared to wet roads of ***$0.1052*** per VMT for passenger cars and ***$0.5224*** per VMT for commercial vehicles.

Using National VMT values published by the USDOT Bureau of Transportation Statistics commercial vehicles may be approximately 10% of the total highways VMT[12]. This can then be used to calculate an overall delay cost for snowy roads compared to wet roads of ***$0.1469*** per VMT. This value can be used for the cost savings per winter maintenance treated VMT with the understanding that winter maintenance treatments produce an approximate effect of snowy/icy roads to wet/bare roads.

Using methods proposed by McKeever et al. (1998) that RWIS presence leads to a 10% increase in time the roads are wet instead of icy/snowy: the delay cost savings of RWIS presence alone is then ***$0.0147*** per VMT. Half of this rate will be used for "fair" to "good" RWIS coverage improvements.

Using the findings of another study by Blackburn et al. (1994) that proactive anti-icing leads to a 20% increase in time the roads are wet instead of icy/snowy: the delay cost savings of using proactive inti-icing compared to traditional deicing and snow removal is then ***$0.0294*** per VMT.

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[10] "Snow and Ice" FHWA Road Weather Management Program. http://www.ops.fhwa.dot.gov/weather/weather_events/snow_ice.htm Accessed April 21, 2016

[11] Schrank, D., Eisele, B., Lomax, T., and Bak, J. "2015 Urban Mobility Scorecard." Texas A&M Transportation Institute and INRIX, 2015.

[12] "Table 1-35: U.S. Vehicle-Miles" USDOT-RITA-BTS. http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_01_35.html accessed April 21, 2016

9) APPENDIX D: WINTER MAINTENANCE COSTS

MDT total yearly winter maintenance costs are approximately $43.48M for 2016[13].

Typically about 40% of winter maintenance costs are for labor, 30% are for equipment, and 25% are for materials (Boon & Cluett, 2002[14]).

These proportions result in approximate total labor costs of ***$17.39M*** and materials costs of ***$10.87M***.

[13] "About MDT" Montana Department of Transportation. http://www.mdt.mt.gov/mdt/docs/about-mdt.pdf Accessed April 21, 2016.
[14] Boon, C. and Cluett, C. "Road Weather Information Systems: Enabling Proactive Maintenance Practices in Washington State." Report WA-RD 529.1 for Washington State Department of Transportation. 2002.

10) APPENDIX E: IDAHO EXPERIENCE

The percent of time that mobility was not significantly impeded (as monitored by automated performance measures using non-invasive sensors that utilize grip level readings and normalized by storm severity) in Idaho improved from the baseline season of 28% to the most recently report 3-year average of 62% (Koeberlein, 2015). This 34% improvement in the time mobility is not impeded is analogous to the time grip levels remain high during winter storms.

Using this 34% improvement with crash cost reduction methods in Appendix A yields an approximate crash reduction savings of ***$0.2101*** per applicable VMT for utilizing non-invasive sensors and automated performance measures.

Similarly, using this 34% improvement with delay cost reductions in Appendix C yields an approximate delay reduction savings of ***$0.0499*** per applicable VMT for utilizing non-invasive sensors and automated performance measures.

Idaho has also reported significant winter maintenance cost reductions as a result of their RWIS program (Koeberlein, 2015). Specifically, a 40% materials savings has been documented (ITD, 2009[15]). A conservative estimate of ***20%*** materials savings is used for applicable scenarios.

[15] Idaho Transportation Department. "How Idaho's non-invasive RWIS network is paying for itself while helping to set new standards for improved service and operations." ITD Transporter, January 30, 2009.

11) APPENDIX F: MOBILE RWIS COVERAGE

<u>During every 30 minute period</u>:

Fixed RWIS Site:

- 25 mile coverage radius (*in accordance with prior literature review findings*)
- 30 minute weather observation frequency (*current MDT polling-reporting practice*)

Mobile RWIS:

- A mobile RWIS measurement has the same geographic coverage as a fixed site (*assumed*)
- 50 mph average vehicle speed (*assumed*)

Then a mobile RWIS would have approximately ***1.5 times*** the geographic coverage of a fixed RWIS (for a linear roadway negating coverage perpendicular to road) as shown in Figure 2.

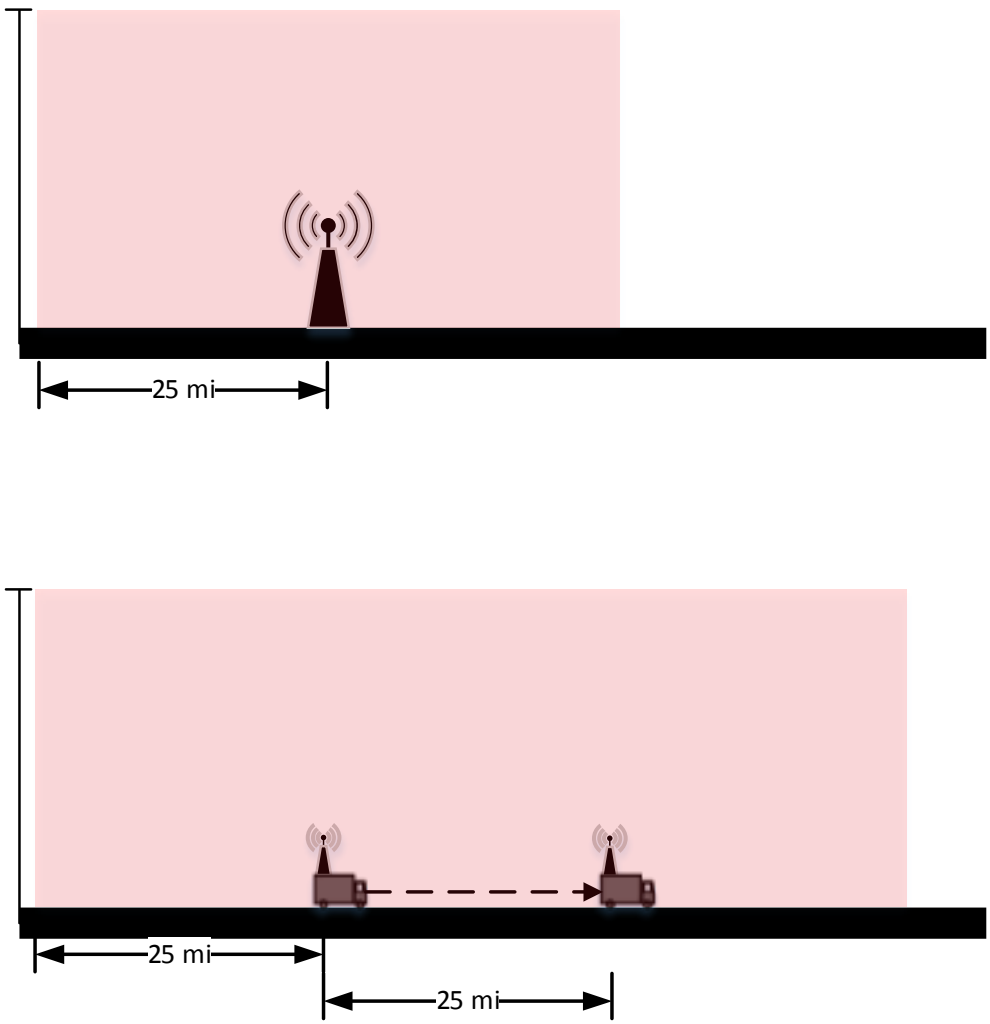

Figure 2: Geographic Coverage of Fixed (top) and Mobile (bottom) RWIS