Anti-Icing Field Evaluation

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Anti-icing is the snow and ice control practice of preventing the formation or development of bonded snow and ice by timely applications of a chemical freezing-point depressant. This definition derives from U.S. snow and ice control practice observed in anti-icing field evaluations for the Strategic Highway Research Program and FHWA. The FHWA project and the implications of its results for implementation of an anti-icing program are described. This definition and the diversity of operations that can lead to anti-icing success are the focus of this paper. A framework for communication and technology transfer among practitioners is provided to complement guidance contained in the project's manual of practice.

"Anti-icing is the snow and ice control practice of preventing the formation or development of bonded snow and ice by timely applications of a chemical freezing-point depressant." This definition of highway anti-icing comes from *Manual of Practice for an Effective Anti-Icing Program: A Guide for Highway Winter Maintenance Personnel* (*1*). It derives from U.S. snow and ice control practice observed during the Strategic Highway Research Program (SHRP) project H-208, Development of Anti-Icing Technology (*2*), and the Federal Highway Administration (FHWA) Test and Evaluation Project 28 (T&E 28), Anti-Icing Technology, which was managed by the Cold Regions Research and Engineering Laboratory (CRREL) under contract to FHWA (*3*). The definition is notable because it implies both specific and nonspecific actions for implementation. In particular, although it specifies anti-icing as a practice based on chemical application for preventing the formation or development of a bond between pavement and snow or ice, it does not suggest the type of chemical operations to perform or how operational decisions should be made. This generality is intentional, because the maintenance operations of T&E 28 clearly showed that the desired anti-icing result can be achieved by using a variety of operational methods and decision-making tools. For example, one group may be successful using rock salt or prewetted rock salt as the applied chemical freezing-point depressant, but another group operating under similar conditions may be successful with a different chemical in liquid form. The stated intention, to prevent the formation or development of bonded snow or ice, must be clarified. Preventing the *formation* of bonded snow or ice means that the bond simply does not form. Preventing the *development* of bonded snow or ice means that, while snow or ice is bonded to the road during some period of the storm, the strength of the bond is mitigated. In the case of formation, although bare pavement conditions are often achieved, slush, loose snow, and nonbonded packed snow are also commonly observed. In the case of development success can be achieved even with sustained periods of weakly or moderately bonded snowpack or ice. Thus, although a "successful" anti-icing operation can result in a variety of conditions that are slippery, these conditions are always more desirable than is strongly bonded snow or ice, which is difficult to remove and thereby provides low traction for extended periods. It may be surprising that anti-icing success can mean conditions ranging from slush to loose snow to packed snow. Yet this was observed during T&E 28. The positive implication is that anti-icing practices, although diverse, can be further engineered to achieve a desired target level of effectiveness. For example, with adequate resources, operations on one highway might be designed to prevent bonded snow or ice at all times, whereas operations on another highway might be designed to prevent development of a strong bond so that all snow or ice can be readily removed within a certain time, perhaps, after the end of a storm or before a heavy traffic period.

By focusing on the formation and development of the bond, the definition centers on the effectiveness of anti-icing practices rather than on reduced costs or any other secondary objective or benefit. This focus is consistent with the observed practices of T&E 28 participating agencies, which, because of the demanding effectiveness requirements of high service levels, have been instinctively implementing elements of anti-icing practices for years. Anti-icing above all should be seen as a practice that, because of its preventive nature, provides a high level of maintenance effectiveness, and not as a practice that automatically results in lower cost. The secondary issue of savings depends on current practice—for example, what level of service current practice supports, what materials it uses, whether it provides more deicing than anti-icing, and what information sources it uses. Nonetheless, because anti-icing has evolved within U.S. practice to mean a modern snow and ice control strategy that makes systematic use of new technologies including road weather information systems (RWISs), site-specific weather and pavement temperature forecasts, and sophisticated spreader and plowing equipment, it has become synonymous with efficiency. Indeed, the modern practice of anti-icing provides a maintenance manager with two major capabilities: the capability to maintain roads in the best condition possible during a winter storm and the capability to do so efficiently. As a consequence, anti-icing has the potential to provide the benefit of increased traffic safety at the lowest attainable cost. However, to achieve this benefit the maintenance manager must follow a systematic approach to snow and ice control and must ensure that the performance of the operations is consistent with the objective of preventing the formation or development of bonded snow and ice—generally throughout the entire storm. Such an approach requires considerable judgment, methodical use of available information sources, and operations that anticipate or respond promptly to icing conditions. The initial definition reflects this approach in its reference to *timely* applications of chemicals.

An anti-icing field evaluation program was designed by CRREL and conducted under T&E 28. This paper briefly describes the field evaluation and implications of the results for implementation of an anti-icing program. By focusing on the definition of anti-icing and the diversity of operations that can lead to anti-icing success, the paper offers practitioners a broad framework for communication and technology transfer. Additional descriptions of the field evaluation and its results are contained in reports of the project (*1,3*).

EXPERIMENTAL AND DATA ANALYSIS TECHNIQUE

The field evaluation of T&E 28 included a two-winter, experimental anti-icing study at 16 sites in 15 states—California, Colorado, Iowa, Kansas, Maryland, Massachusetts, Minnesota, Missouri, Nevada, New Hampshire, New York, Ohio, Oregon, Washington, and Wisconsin—and an analysis of the experimental data. The evaluation comprised field operations and experiments conducted by state highway agency personnel, and the data analysis consisted of graphical and statistical analysis conducted by CRREL.

The general approach of the anti-icing experiments, and many of the specific techniques of the experiments, followed the experimental concept and techniques of the preceding SHRP project H-208 (*2*). As they were in SHRP H-208, the experiments were conducted at the sites by using different anti-icing and conventional treatments. They were conducted during a variety of storm events that reflected the nature of storms at each site and at the various geographical locations over the two-winter period of the study. An experiment consisted of anti-icing operations on a test section, conventional operations on a control section, documentation of the operations, and data collection during a single storm. The anti-icing operations of T&E 28 were conducted according to treatment strategies that were developed by personnel at each site so that the results would provide knowledge of locally designed anti-icing programs. This approach also furthered the implementation objectives of the project. The conventional operations were intended to reflect the standard practice at the site, with no influence from the anti-icing operations.

More than 200 storm data packages were submitted by the states for the 2 years of the study, and considerable documentation was provided in each storm package. Documents included weather and pavement temperature forecasts; RWIS and other weather data; logs of the operations and data collection; traffic data; and, for selected sites and storms, cost data. Operation logs included the type, proportions or concentration, and application rate of each major chemical component of all chemical treatments, the snow plowing operations, the type and application rate of any abrasives that were placed, and any other operations.

The on-road data collection consisted primarily of precipitation observations, friction measurements, and pavement condition observations. The friction measurements at all sites were made with a commercially available deceleration-type friction meter that was installed in an agency sedan or pickup truck used as the measurement vehicle. The friction measurements and pavement condition observations were focused on the wheel paths of the driving lanes, and several measurements and observations were made during each pass of the measurement vehicle. An additional observation was made to judge whether the driving lane of the test section or the driving lane of the control section provided the better traction, or whether there was no perceivable difference.

The data analysis examined and interpreted the operations and their results, established significant differences between the effectiveness of test and control operations, established conditions under which anti-icing is effective, and developed statistically based conclusions and recommendations for practice. Storm data sets were analyzed individually and in blocks of a given season and site. Results from a single storm provided a "close-up" of the operations and their effectiveness, and results from several storms at a site allowed the "big picture" to appear.

The fundamental results from a single storm were the graphical data histories and the operations summaries. Data histories of two storms and two sites are given as examples in Figures 1 and 2. Figure 1 displays data from the January 23–25, 1995, storm at the New York site, located in the Rochester metropolitan area a few miles south of

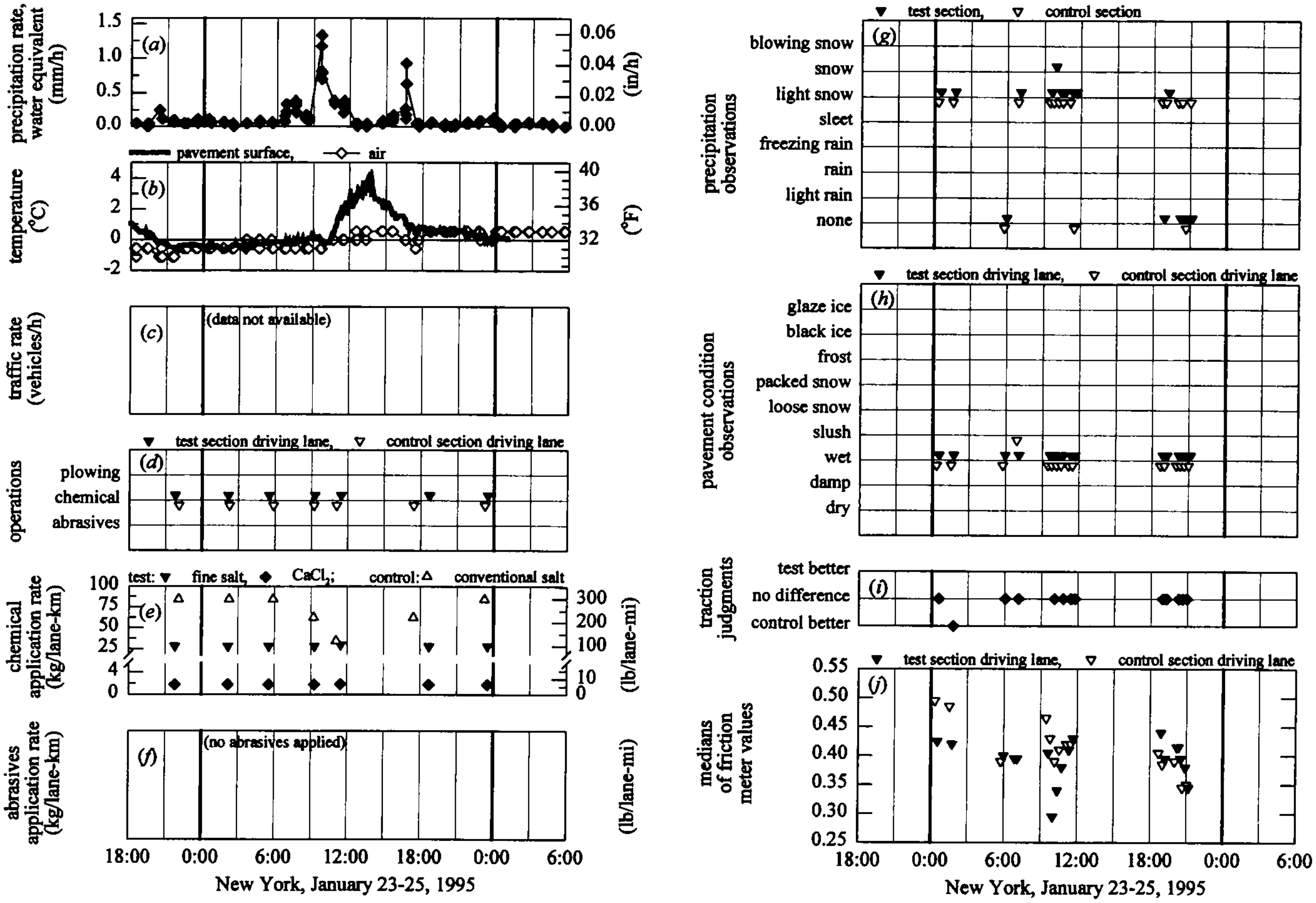

FIGURE 1 Data histories of storm of January 23–25, 1995, New York site, asphalt pavement section: (*a*) water equivalent precipitation rate, (*b*) temperature, (*c*) traffic rate, (*d*) operations, (*e*) chemical application rate, (*f*) abrasives application rate, (*g*) precipitation observations, (*h*) pavement condition observations, (*i*) traction judgments, (*j*) medians of friction meter values.

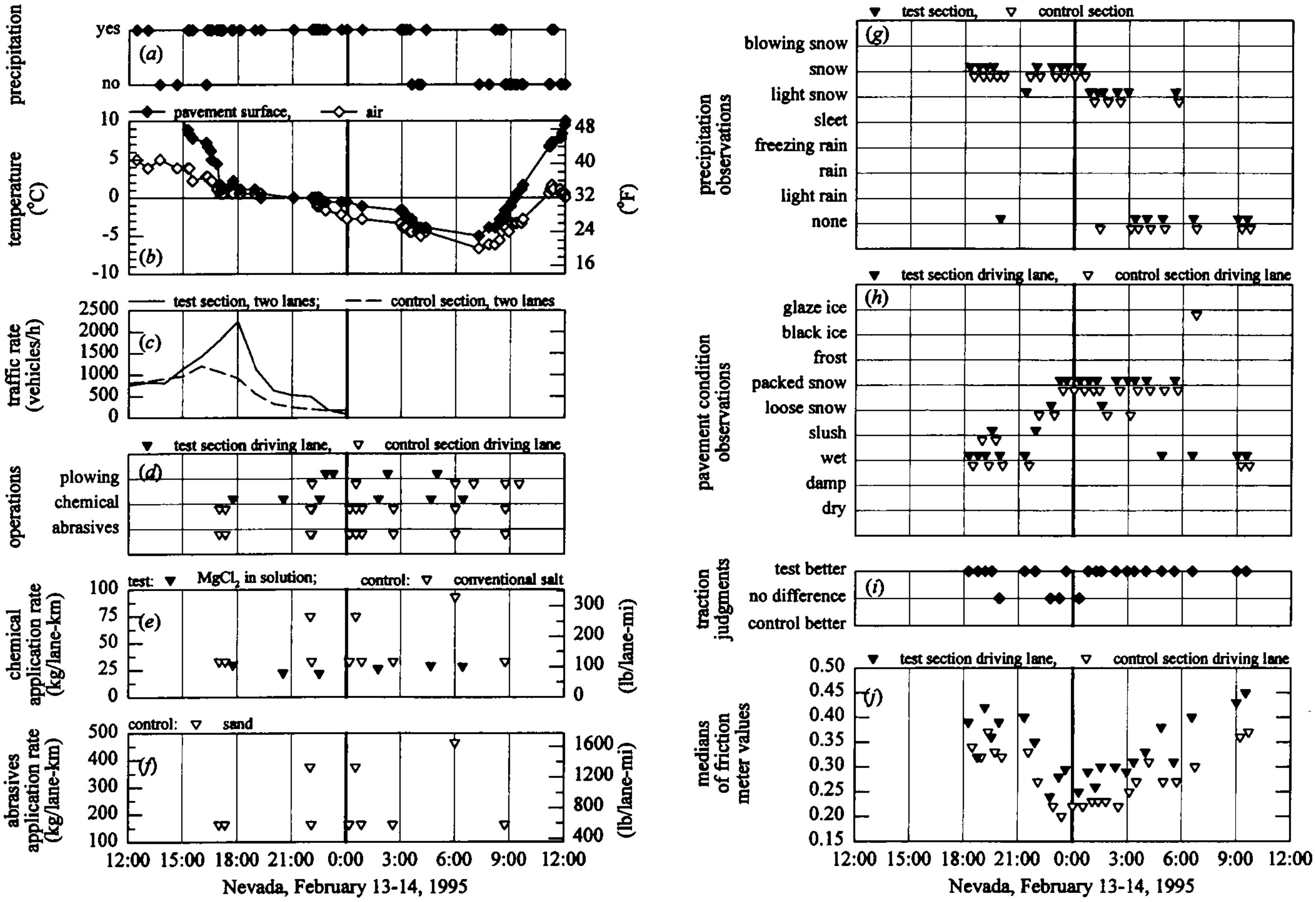

FIGURE 2 Data histories of storm of February 13–14, 1995, Nevada site: (*a*) precipitation, (*b*) temperature, (*c*) traffic rate, (*d*) operations, (*e*) chemical application rate, (*f*) abrasives application rate, (*g*) precipitation observations, (*h*) pavement condition observations, (*i*) traction judgments, (*j*) medians of friction meter values.

Lake Ontario in the city of Webster, and Figure 2 contains data histories from the February 13–14, 1995, storm at the Reno, Nevada, site.

Figures 1 and 2 each contain 10 graphs. The left columns are histories of (*a*) precipitation from the RWIS data—that is, the precipitation rate in Figure 1 and a yes-or-no indication of precipitation in Figure 2; (*b*) pavement surface and air temperatures, also from the RWIS data; (*c*) traffic rates on the test and control sections; (*d*) the plowing, chemical, and abrasives operations on the test and control section driving lanes; (*e*) the chemical application rates; and (*f*) the abrasives application rates. The right columns present histories of (*g*) the precipitation observations, (*h*) the pavement condition observations, (*i*) the traction judgments, and (*j*) the friction meter values, all of which were recorded by the driver or passenger in the measurement vehicle. The observation graphs display categories of precipitation and pavement condition that could be selected during the on-road data collection.

All data histories developed for the project included many features of the graphs in Figures 1 and 2:

- The time scale appears at the bottom of each column. It is shown with grid lines at 3-hr increments and a heavier grid line at midnight or 0:00.
- Only driving lane operations are shown.
- All operations, observations, traction judgments, and friction data are plotted at the time of the beginning of the pass.
- The number of lanes used to calculate the application rates is the integer number of lanes over which material is spread.
- All application rates of chemical solutions, whether for prewetting of solids or straight liquid applications, present the rate of the solute, or dry chemical, in the solution.
- On the operations and observations graphs, test section data points are indicated slightly above control section points.

TABLE 1 Summary of Driving Lane Operations, New York, January 23–25, 1995

	Section	
	Test	Control
Total number of passes:	7	7
Number of passes with plowing:	0	0
Number of passes with fine salt application:	7	0
Total application of fine salt, kg/lane-km (lb/lane-mi):	199 (707)	0
Number of passes with conventional salt application:	0	7
Total application of conventional salt, kg/lane-km (lb/lane-mi):	0	497 (1763)
Number of passes with application of calcium chloride prewetting solution:	7	0
Total application of calcium chloride, kg/lane-km (lb/lane-mi):	13 (45)	0
Number of passes with abrasives application:	0	0
Total application of abrasives, kg/lane-km (lb/lane-mi):	0	0

- Precipitation and observation data points represent the mode—the most frequent observation—of the multiple observations made during a pass.
- The friction value data point plotted is the median—the 50th percentile—of the multiple friction measurements made during a pass. The friction values are those of maximum braking action, of either conventional or antilock braking systems.

Summaries of the driving lane operations during the two storms are presented in Tables 1 and 2. Each table lists the total number of passes as well as the number of passes with plowing, chemical, and abrasives operations. The total applications of the various materials are given as well, presented per unit lane-kilometer (lane-mile). If a pass included more than one task, for example, if plowing and chemical operations were conducted simultaneously, or if a mix of abrasives and chemicals was applied, the tables list separately the component tasks or applications.

Storm Data Interpretations

The storms depicted in Figures 1 and 2 were chosen to illustrate the diversity of operations in the project and the depth of data interpretation conducted for the project. Comments based on the full data analysis for each storm are presented in the following sections.

New York, January 23–25, 1995

At the New York site the test and control sections were 11-km (7-mi) sections of NY-104. The eastbound lanes were the test section and the westbound lanes were the control. Throughout the season the chemical operations on the test section were primarily applications of fine salt prewetted with a calcium chloride ($CaCl_2$) solution, while dry conventional rock salt was used mainly in the control section operations. The operations and data collection were conducted by New York State Department of Transportation (NYSDOT) maintenance personnel.

The January 23–25 storm was a light snow storm with one period of heavier snow. Before the event, lake effect snow flurries and showers were forecast to begin in the afternoon hours on January 23 and continue into the next day. Accumulations of up to 50 mm (2 in.) were predicted. The pavement temperature was forecast to drop to and below freezing after 9:00 p.m. and remain below freezing until the morning peak hour. The pavement temperature indicated in Figure 1(*b*) reflects this prediction, hovering just below freezing during the ear-

TABLE 2 Summary of Driving Lane Operations, Nevada, February 13–14, 1995

	Section	
	Test	Control
Total number of passes:	11	12
Number of passes with plowing:	5	6
Number of passes with application of magnesium chloride solution:	6	0
Total application of magnesium chloride, kg/lane-km (lb/lane-mi):	159 (565)	0
Number of passes with conventional salt application:	0	10
Total application of conventional salt, kg/lane-km (lb/lane-mi):	0	474 (1682)
Number of passes with abrasives application:	0	10
Total application of abrasives, kg/lane-km (lb/lane-mi):	0	2367 (8398)

lier part of the operations and rising slightly above freezing after the morning peak period on January 24 to well above freezing during the midday hours. In the evening hours of January 24 the temperature dropped again toward freezing. Traffic counts were not available for the storm, but workday traffic on the test section driving lane typically reaches 1,000 vehicles per hour (vph) in the morning peak period, fluctuates between 500 and 1,000 vph midday, and increases to 1,500 vph in the afternoon peak period.

As indicated in Figure 1(*d*) and Table 1, test section applications of the prewetted fine salt, and control section applications of conventional rock salt, were the only operations conducted during the January 23–25 storm. No abrasives were applied, and because conditions did not warrant them, plowing operations were not conducted. The initial fine salt–$CaCl_2$ solution application was made about 2 hr after the pavement temperature dropped to freezing and snowfall began. Snow covered the highway at the time of the application, according to storm records. Although observations and friction measurements were not made until more than 4 hr after the beginning of the storm, the supervisor's log and other data suggest that earlier operations were not warranted and the initial operation was indeed preventive. Control section salt applications were begun soon after the test operations. Throughout the storm there was similar timing of the chemical applications on both test and control. This timing was not unusual at the New York site and indicates that preventive anti-icing practices are built into conventional operations. In the same number of passes, however, more than twice as much chemical was used on the control section driving lane as on the test section driving lane (Table 1).

As indicated by the predominantly wet pavement conditions in Figure 1(*h*) and the fact that bonded snow and ice was clearly prevented, both the test and the control operations were successful anti-icing operations. Although these were developmental anti-icing operations, very little obscures their success. A January 24 late-morning increase in snowfall resulted in a temporary drop in friction on both sections, although the drop was greater on the test section, perhaps reflecting the lower chemical rate used there. A subsequent rise in pavement temperature above freezing resulted in a rapid increase in friction. A miscommunication resulted in the application of chemicals on both the test section and control section driving lanes after this rise in pavement temperature, although the supervisor had recognized that the application was not necessary and had sent trucks only to plow shoulders.

Although more than twice as much chemical was used on the control section driving lane as on the test section, the observation, traction, and friction data do not indicate significantly greater control section effectiveness, suggesting that the test section fine salt application rate at an average of approximately 28 kg/lane-km (100 lb/lane-mi) is more appropriate for light snow and relatively high pavement temperature than the control section conventional rock salt application rate at an average of 70 kg/lane-km (250 lb/lane-mi).

Nevada, February 13–14, 1995

The Nevada test and control sections were 10-km (6-mi) sections of US-395 in the northbound and southbound directions, respectively. For the season the chemical operations on the test section were mostly applications of a magnesium chloride ($MgCl_2$) solution, and a conventional 1:5 rock salt–sand mixture was used on the control section. The operations and data collection were conducted by Nevada Department of Transportation (NDOT) maintenance crews.

The precipitation observations in Figure 2(*g*) show that this storm consisted of several hours of moderate and heavy snowfall followed by light snow. Maintenance crews referred to the storm as the "St. Valentine's Day Massacre." Forecasts called for light rain changing to a snow-rain mix at 5:00 p.m. on February 13 and pavement temperatures dropping to freezing at 6:00 p.m. The mix was predicted to change to all snow during the evening and last into the following day with accumulations up to 150 mm (6 in.), and freezing or below-freezing pavement temperatures were predicted to remain until after daylight the next morning. The forecasts were accurate.

The traffic rate data in Figure 2(*c*), although not complete, reflect peak hour directional variations of the afternoon of February 13. On the basis of traffic records from other days, data from February 14 would probably have shown a morning peak period with two-lane control section rates peaking at close to 2,500 vph and two-lane test section rates close to 1,000 vph.

On the test section the $MgCl_2$ solution was initially applied after light snow had begun and the road was wet. The timing was based on rapidly falling pavement temperature, which was expected, and provided a good demonstration of the use of RWIS data and RWIS-based forecasts for timing decisions. Subsequent $MgCl_2$ applications were made on the basis of observations of conditions and RWIS pavement temperature and chemical concentration data. Control section sand and salt applications were begun just before the test operations. Like the timing of the initial New York operations, this timing was not unusual and illustrates the preventive nature of the Nevada conventional operations and their reliance on RWIS and other information sources. Table 2 shows that throughout the storm three times as much chemical was used on the control section driving lane as on the test section driving lane. No abrasives were used on the test section, whereas 2367 kg/lane-km (8,398 lb/lane-mi) of sand was used on the control section driving lane.

The percentage breakdown of all test section pavement condition observations was 42 percent packed snow, 37 percent wet, 9 percent slush, 8 percent loose snow, and 3 percent damp. On the control section the breakdown was 44 percent packed snow, 22 percent wet, 16 percent loose snow, 14 percent slush, and 4 percent glaze ice. The chi-square statistical test (*4*) showed a significant difference between the test and control observations. This difference is probably because although both operations resulted in the development of undesirable sustained packed snow conditions, the test section operations resulted in more wet and fewer loose snow or slush observations, which is desirable.

Figure 3 depicts the friction distributions for the February 13–14 storm and for the 1994–1995 season. Figure 3(*a*) is a graph showing Tukey box plots of test section and control section friction data from the storm, which are distributions of all measured friction values of the sections during the storm. The top of a box indicates the 75th percentile (i.e., 75 percent of the observations were at or below that friction value on the left scale), and the bottom indicates the 25th percentile. The line inside a box is the median, or the 50th percentile. The single line above a box is the 90th percentile and that below a box the 10th percentile. The distributions provide a graphical comparison of the test and control section data. A further comparison was provided by results of the Mann-Whitney rank sum statistical test (*4*), which reveals whether the medians of the test and control friction are significantly different. As indicated in Figure 3(*a*), the test found a significant difference. Both the distribution and the median were higher for the test section friction data, reflecting the Figure 2(*j*) data showing that the test section friction was higher throughout the storm.

Figure 3(*b*) shows box plot distributions from the combined friction and observation data of 14 storms of the season. The variation of the distributions with pavement condition category is reasonable and provides confidence in both the friction and pavement condition data as independent effectiveness measures. By comparison of the storm distributions of Figure 3(*a*) and Figure 3(*b*), the test section median value of the storm was typical of a slush pavement condition, whereas the control section median friction was typical of loose snow or packed snow conditions. Although more chemical was used on the control section, and sand was used only on the control section, the overall storm test section friction was higher, reflecting a better pavement condition. In addition to the friction and observation data showing better test section conditions, the measurement vehicle operator's judgments graphed in Figure 2(*i*) suggest that the test section usually had better traction.

The development of packed snow on both test section and control section driving lanes occurred during a period of heavy snow and low nighttime traffic. At 10:30 p.m. on February 13, a test section application of the $MgCl_2$ solution was made onto loose snow just before the development of pack. The operator noted that the road was "covered" and snowfall was "heavy." Plowing did not precede this application, however.

During the period of packed snow on both sections, much more chemical was used on the control section driving lane than on the test section driving lane, and a large quantity of sand was placed on the control section driving lane. The greater chemical amounts and use of abrasives during this time did not lead to better friction or traction, or an earlier breakup of the pack,

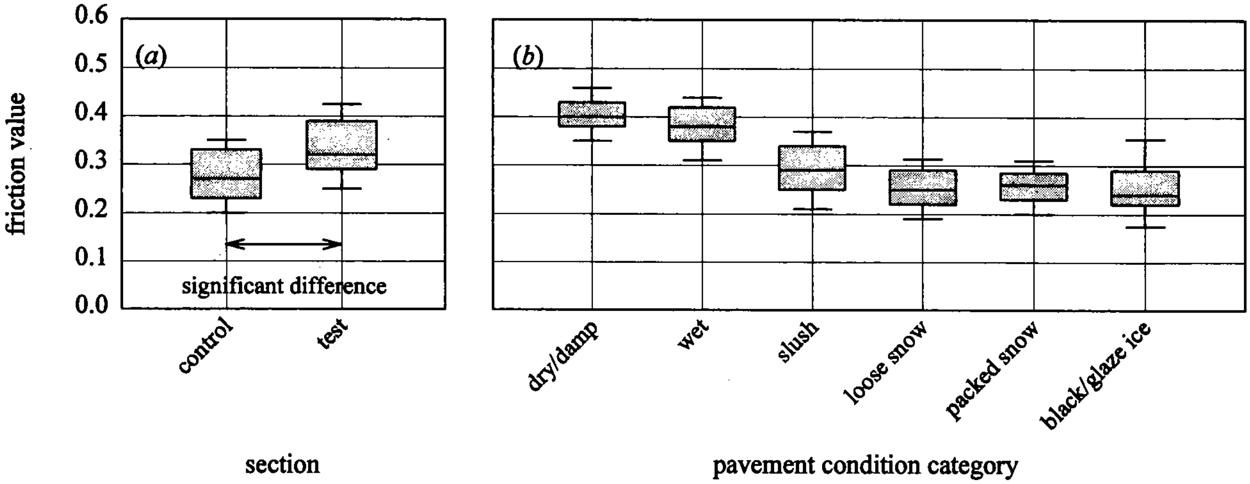

FIGURE 3 Nevada friction distributions: (*a*) as function of section for February 13–14, 1995, storm, and (*b*) as function of pavement condition category for 1994–1995 season.

however. In fact, the packed snow broke sooner on the test section. Regular plowing operations, moderate applications of the $MgCl_2$ solution, and precipitation changing from moderate snow to light snow to no snow led to the test section breakup *before* peak hour traffic. For the test section, traffic was not a factor. The later breakup of the control section snowpack coincided with a rise in pavement temperature and peak hour traffic.

The Figure 2 data indicate that the application rates of the $MgCl_2$ solution were too low or the number of passes before the development of the packed snow were too few to prevent a bonded snowpack with the snowfall, temperature, snow moisture, and traffic conditions of the storm. Plowing ahead of liquid applications appears essential when snowfall is heavy and with conditions of loose snow on the pavement. Even so, the test section operations resulted in an apparently weaker and easier-to-clear compacted snow–pavement bond than did the control section operations. For the control section abrasives applications, no evidence in Figure 2(*j*) indicates a short- or long-term increase in test section or control section friction caused by their use. In fact, during the storm the measurement vehicle operator described a friction test after an abrasives application as "sliding on sand," suggesting that the abrasives application had a detrimental effect on friction.

Discussion of Results

Beyond the specifics of the individual events, the two storms reveal much about the nature of the project and how the results could be used to develop recommendations for practice. As typified by the New York and Nevada operations, very few of the conventional operations of the project were traditional deicing operations in which, typically, plowing and chemical applications are initiated to remove already bonded snow or ice. In fact, several of the conventional operations were high service level operations that in many ways were preventive in nature and yielded insight into the anti-icing process. This is probably because of prior implementation by state and site personnel of technology such as RWIS and site-specific weather and pavement forecasts, anti-icing practices developed during SHRP H-208 (*2*), and other preventive techniques over the course of several years. Nonetheless, relative to the operations specified in the manual of practice (*1*), even the anti-icing operations of the project represent development phase operations. This is precisely because the results of the field evaluation provided the basis for the development of comprehensive guidance for implementing the anti-icing process at efficient chemical application rates.

The nature of the project is further reflected by the timing of the initial operations of the two storms. Although prestorm chemical applications can certainly be effective, anti-icing has previously been associated wholly with this timing of the initial treatment. In neither storm example was the initial test section chemical application made in advance of precipitation. This was the intentional strategy of the supervisors, and both operations were successful—the first by preventing the formation of the bond and the second by preventing the development of a strong bond. By relying on local personnel to develop their own anti-icing strategies, the project was able to demonstrate the range of application timings that can either prevent the bond altogether or reduce its severity. More important, by the design of the experiments the project was able to build such field-demonstrated lessons into the manual of practice.

Beyond timing of the initial chemical application, further indication of the diversity of successful operations is provided by classifying the various chemical treatments. In the two storms presented, four general chemical treatment types were used: a dry solid chemical, a prewetted solid chemical, a dry solid chemical in a mix with abrasives, and a chemical solution. Together with a prewetted chemical–abrasives mix, these were the types used in the project. Three of these—solid chemical, liquid chemical, and prewetted solid chemical, as they are classified in the manual of practice (*1*)—were demonstrated to be efficient anti-icing treatments under a variety of conditions and are covered in the manual's guidance. However, as the results did not show any consistent advantage to the use of abrasives with chemicals, there are no grounds for recommending their use, and therefore no guidance is given.

CONCLUSIONS

Improvements in snow and ice control have long been made by winter maintenance forces by shifting toward preventive instead of reactive practices. Recognizing this, the anti-icing field evaluation conducted under FHWA T&E 28 accommodated both conventional and modern preventive practices and, by analysis of the operations and their effectiveness, identified the diversity of operations that can support the bond-prevention objective of anti-icing. The result is a field-derived manual of practice that provides comprehensive guidance for implementing efficient anti-icing practices. Although information sources, technology, and education are required to use the guidance—particularly site-specific forecast information and pavement temperature, efficient spreaders to apply chemicals at desired rates, and anti-icing training for maintenance crews—the guidance can readily be implemented to provide a high level of service. For managers involved in implementing anti-icing practices, it is well to recognize that both conventional and high-technology preventive practices, intelligently applied, can be the foundation on which to build a successful program.

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