Report No. CDOT-DTD-R-2002-5
Final Report

Cost of Sanding

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DEPARTMENT OF TRANSPORTATION
RESEARCH

June 2002

COLORADO DEPARTMENT OF TRANSPORTATION
RESEARCH BRANCH

Cost of Sanding

by

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Executive Summary

This study marks the first collaborative research between Colorado DOT and the Colorado auto insurance industry to address the cost issues resulting from the use of sand as a roadway traction enhancement material in inclement winter weather. Traditionally sand was spread on snowy and/or icy pavement to enhance the roadway traction. This has been shown to be costly in many respects including roadway maintenance, vehicle damage (particularly to windshields), and environmental and human health.

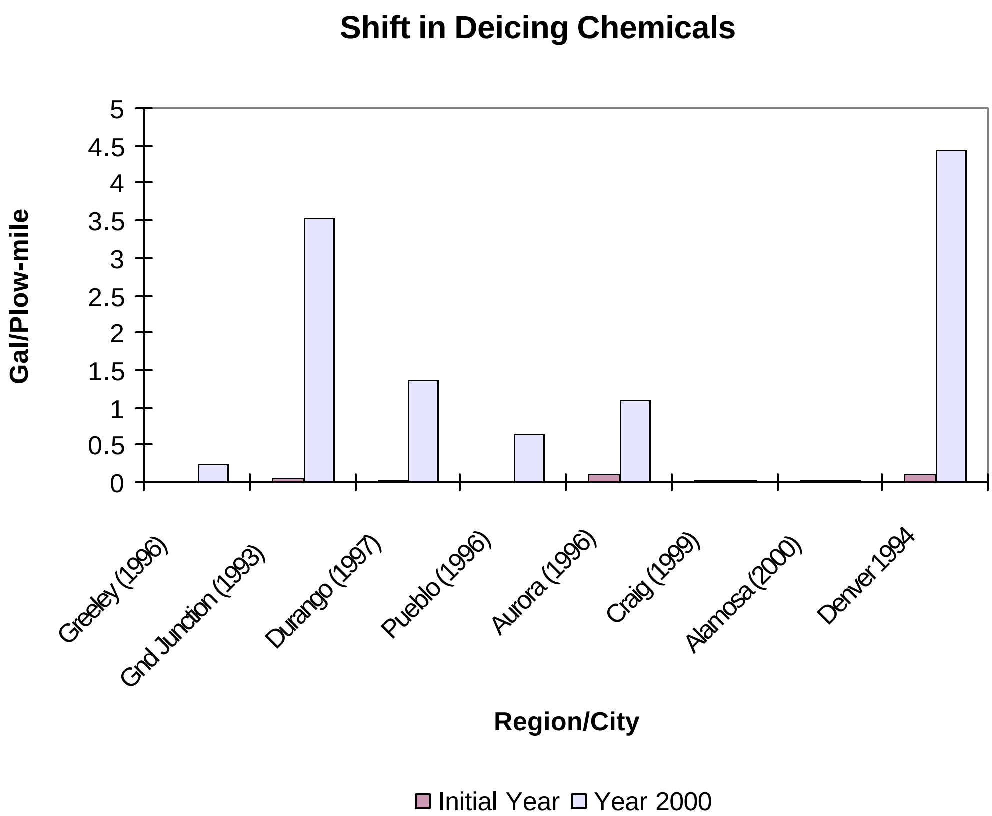
Vehicle grinding of sand allows fine particulate matter, PM-10 (or PM-2.5), to become airborne when dry, and causes river silting during snow melt via surface drainage. Particulate matter causes respiratory problems in humans and river silting chokes rivers and causes ill effects to the river ecosystem. The Center for Geotechnical Engineering Science (CGES) at the University of Colorado at Denver completed a CDOT-sponsored study on "Environmentally Sensitive Sanding and Deicing Practices" in 1994. The study recommended the formulation of an optimal practice that minimizes the use of sand and increases the use of environmentally friendly chemicals for the purpose of enhancing winter highway traction and maintaining both environmental health and human respiratory health. The recommendation has been implemented since 1994. This resulted in a winter roadway maintenance policy shift for Colorado DOT and municipalities from strictly using sand to the increasing use of deicing/anti-icing chemicals. The shift has had a direct impact on all issues related to safety, cost, environment, and human health. It has improved the Colorado air quality, as evidenced in the fact that Colorado has not exceeded the EPA PM-10 standard for the last seven winters, and consequently has positively impacted people's respiratory health and the river ecosystem.

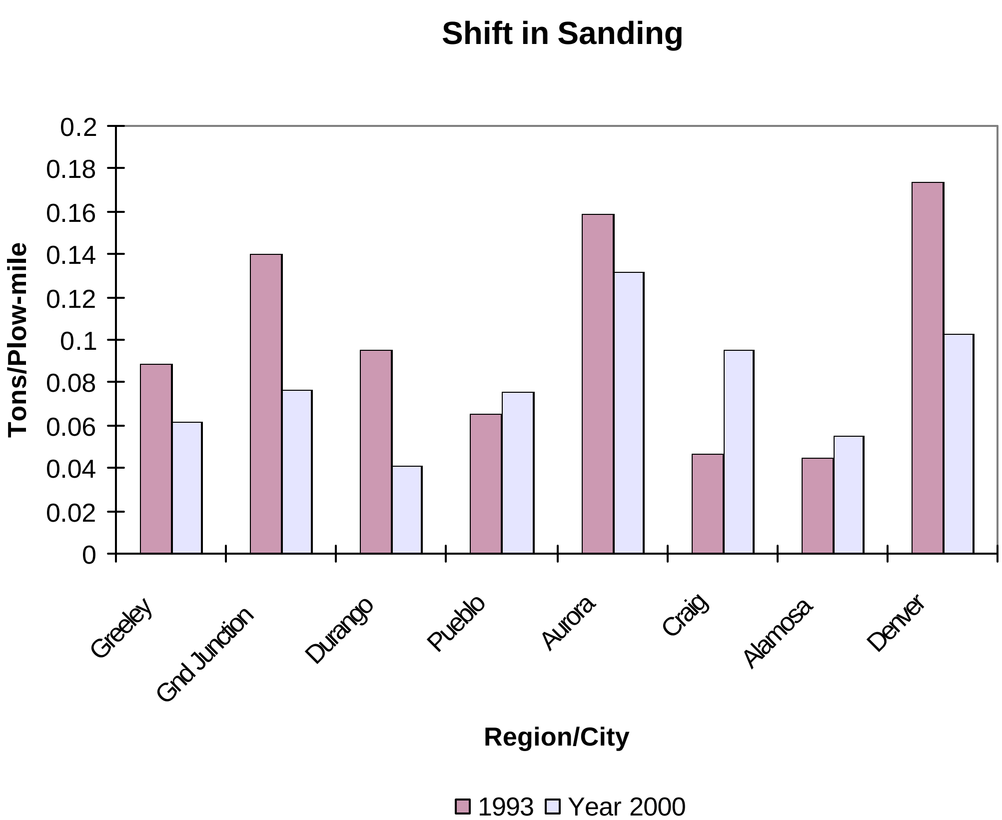
This collaborative study focuses on the cost of sanding to CDOT and to the traveling public. The CDOT annual maintenance budget and expenditures are the basis for the CDOT cost study. The cost is divided into three different categories: materials, labor and equipment. Both regional (or sectional) and statewide use of traction enhancement agents and costs are analyzed. As shown in Table E1, the regions or sections studied initiated the use of deicing chemicals at different times and with different degrees of aggressiveness in the period from 1993 to 2000. The aggressive use of deicing chemicals is accompanied by the significant reduction in use of solid materials including sand, rock salt, and sand/salt mix. Greeley, Grand Junction, Durango, and Denver belong to this category. Aurora has increased its use of deicing chemicals from 0.0992 gallons per lane mile in 1996 to 1.09 gallons per lane mile. However, its use of solids has only been reduced by 17%. Alamosa, Craig and Pueblo all began to use deicing chemicals relatively late and with insignificant impact on the use of solids. Statewide, the use of deicing chemicals has significantly reduced the use of solids. This represents a major shift in the winter roadway maintenance practice. In the last five years, the cost of solid material use has not increased; the cost of deicing chemical use has increased exponentially; equipment and personnel costs have not changed much. The total cost of the winter roadway maintenance has remained relatively unchanged since 1995 except for a couple of incidences where the actual cost significantly exceeded the budgeted cost. In summary, the statewide cost for winter roadway maintenance has remained relatively unchanged while the cost of deicing chemical use has increased significantly. In other words, while the increased use of deicing chemicals has not caused significant impact to the winter maintenance budget, it has contributed significantly to the maintenance of environmental health by reducing PM-10 levels in the air as evidenced by the statewide observation of the EPA PM-10 standard since 1995.

The analysis of the cost to the traveling public is based on the claim cost data provided mainly by Company A and Company B out of the eight Colorado auto insurance companies that sponsored this research on windshield damage cost. The two companies represent total policy counts of about 32% of the industry total as shown in Figure E2 on Market Shares. The industry total statistics can be prorated at a little bit over three times the Companies A and B total. The total windshield damage cost is the sum of the cost of repair and replacement. Figure E3 shows that the statewide industry total windshield damage cost has been increasing at a rate of $6.19 million annually. The statewide windshield damage is projected at around $90 million before the inflation adjustment. The statistics seem to show that the rate of increase is dwindling at a time when the state population increases at an exponential rate and so does the auto insurance policy count.

Table E1 Regional Shift in Winter Roadway Maintenance Practice

Region/Section	Deicing Chemical (gallons/plow-mile)		Solid (sand + salt + sand/salt mix, tons/plow-mile)	
	(Year when deicing chemical use initiated)	Year 2000	Year 1993	Year 2000
Greeley	0.0002 (1996)	0.2441	0.0888	0.0617
Grand Junction	0.0608 (1993)	3.5322	0.1403	0.0768
Durango	0.0353 (1997)	1.3640	0.0949	0.0410
Pueblo	0.0023 (1996)	0.6396	0.0654	0.0756
Aurora	0.0992 (1996)	1.0900	0.1593	0.1315
Craig	0.0143 (1999)	0.0191	0.0467	0.0951
Alamosa	0.0244 (2000)	0.0244	0.0453	0.0553
Denver	0.0944 (1994)	4.4357	0.1740	0.1031


Shift in Deicing Chemicals
Gal/Plow-mile
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Greeley (1996)
Gnd Junction (1993)
Durango (1997)
Pueblo (1996)
Aurora (1996)
Craig (1999)
Alamosa (2000)
Denver 1994
Region/City
Initial Year
Year 2000


Shift in Sanding
Tons/Plow-mile
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Greeley
Gnd Junction
Durango
Pueblo
Aurora
Craig
Alamosa
Denver
Region/City
1993
Year 2000

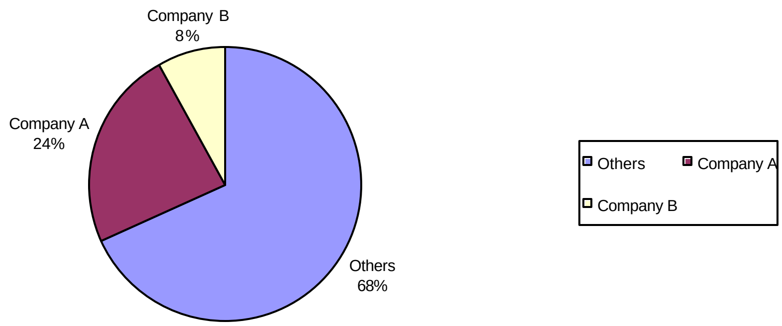


Figure E1 Market Shares of Various Insurance Companies in Colorado

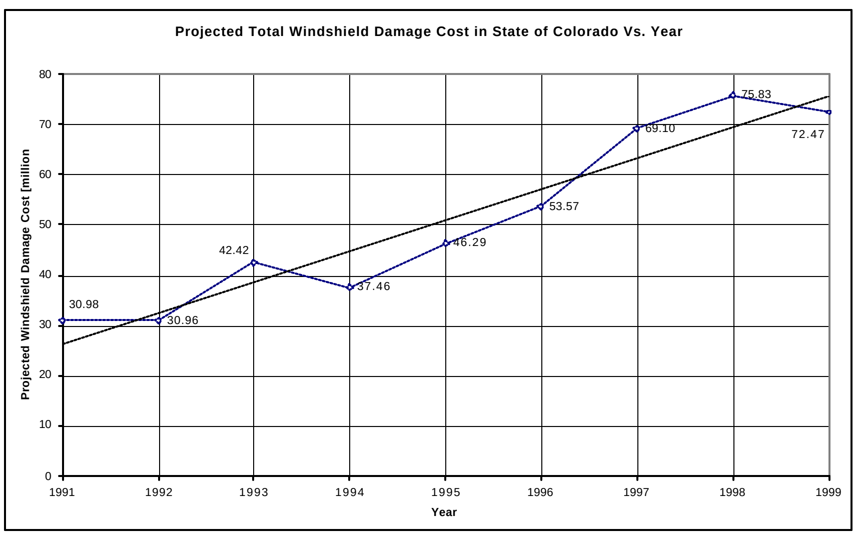


Figure E2 Projected Total Windshield Damage Cost in Colorado Time History

Much research effort was also devoted to the airborne mechanism of sanding rocks, the characteristics of windshield fracture upon impact with a flying rock, and the influence of rock size, shape, density and velocity on windshield fracture. Road tests recorded using a high-speed camera at 20,000 frames per second showed that the rock rebounded vertically from the roadbed as a vehicle cruised over the rocks. The mechanism was confirmed by the dynamic finite element analysis. If a vehicle accelerated over the rocks, the tire-rock-pavement inter-effect mechanism threw the rocks toward an approaching vehicle. Field observations of windshield damage patterns were performed on vehicles parked in both Auraria Higher Education parking lots and the Company A parking lot. It was found that the locations of damage are quite random and the damage patterns come in all different sizes and shapes. The subsequent field tests using a slingshot, shown in Figure E4, were calibrated to show the strain-dependent rock particle velocity. The high-speed camera was also used to provide the images subsequently employed in the velocity calculations. Rocks of different size, shapes, and density were used in the tests. The observations confirmed the damage severity and patterns observed in the hundreds of parked cars used in this research. The severity increases with the size, velocity, and density of rocks. Rounded rocks caused more severe damage than an angular rock of similar size. Angular rocks smaller than 3/8 of an inch cause only minor damage to windshields. It is interesting to note that 3/8 of an inch is also the maximum size in the CDOT specification for sanding rocks.

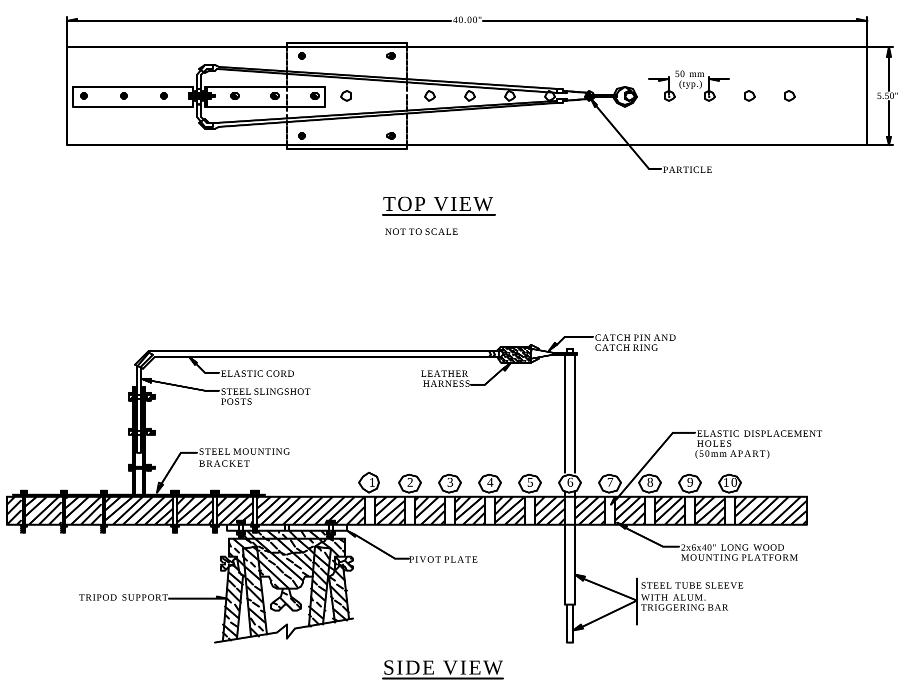


Figure E3 Particle Sling

The recent shift in the winter roadway maintenance of CDOT and various Colorado municipalities of increasing use of deicing chemicals and decreasing use of sands and the CDOT sanding rock specification of no larger than 3/8 of an inch have contributed to the less than expected increase (or even decrease) in the windshield damage cost of the Colorado traveling public before the inflation adjustment. All this took place at a time when Colorado experienced an exponential population increase by 30.57% from 3.294 million in 1990 to 4.301 in 2000 as demonstrated in the U S Census 2000 data. This definitely fares very well for the Colorado traveling public. In conclusion, a well conceived winter roadway maintenance policy and practice makes Colorado highways safer and less costly to the Colorado traveling public.

Implementation Plan

This marks the first research project jointly sponsored by the Colorado Department of Transportation and the Colorado auto insurance industry on the effect of Colorado winter roadway maintenance practices on the CDOT maintenance cost and the windshield damage cost to the traveling public. It is recommended to promulgate the research findings through presentations to CDOT maintenance managers and maintenance crews, at the insurance industry annual meeting, and at the Transportation Research Board annual meeting. The research findings can be used to update CDOT's winter roadway maintenance policy and procedures. Finally, the findings can be presented to the Colorado taxpayers to show them how their tax money is used in assuring their safer driving on the Colorado roadways and reducing the frequency of glass damage caused by road maintenance procedures.

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1. Introduction

1.1 Problem Statement

1.1.1 "Bare Pavement Always Policy"

The major mission of the Colorado Department of Transportation (CDOT) is to provide the best and safest transportation system for Colorado. To achieve this goal, CDOT has adopted a "Bare Pavement Always (BPA)" policy for winter months when the Colorado roadways present unsafe driving conditions. However, this is an ideal situation with its accomplishment depending on timing and weather conditions. During severe winter weather, when BPA is not practical, the combined use of snow and ice removal, sanding, and anti-icing and deicing chemicals is necessary to maintain the best possible roadway traction and highway safety. Traditionally, the primary material used to achieve this goal has been the sand-salt mixture, until a few years ago when some chemical compounds were found effective in preventing ice-pavement bonding and also in melting snow and ice. The use of these chemicals has greatly enhanced the implementation success of the "BPA" policy goals, as demonstrated by the bare pavement shortly after the snow removal and melt because much less sand has been used on Colorado highways. The success of the "BPA" is also demonstrated by the fact that increasingly less windshield damage has occurred in the past six years.

After snowmelt, particularly, when roadways are dry, the sand could become counter productive, cause a reduction in roadway traction and endanger the traveling public. Sand particles could be ground up partially into small particulate matter (PM) with grain size smaller than 10 microns, which is generally called PM-10. Traveling vehicles could then cause the PM-10 to become airborne. Airborne PM-10 has been one of the major reasons for the winter brown cloud and the health concerns, particularly the respiratory system.

To protect the quality of air, the Environmental Protection Agency (EPA) has established a legal limit of PM-10. In the mid 1990's, the City and County of Denver once exceeded the limit three times in one month. Some ski towns experienced similar air quality problems. To mitigate the chance of PM-10 violations, avoid the consequential cut in federal highway funding, and maintain a good air quality, in 1993, CDOT and FHWA funded a research project on "Environmentally Sensitive Sanding and Deicing Practices." The study examined the alternatives for sanding. The study was completed in 1994 by the researchers at the University of Colorado at Denver (UCD). The study recommended, among other things:

- Significantly reduce the use of sand as a traction enhancement material.
- Increase the use of anti-icing and deicing chemicals to partially replace sands to enhance winter roadway traction.
- The complete elimination of sand is both impractical and not feasible. Thus, the optimal winter roadway maintenance would involve an appropriate combination of the use of sand, deicing and anti-icing chemicals, and timely snow plowing and roadway sweeping.

The above recommendations have been implemented throughout CDOT. Its current practice uses much less sand and more deicing chemicals as this study demonstrated. This might have, at least partially, contributed to the good air quality for the last six years.

1.1.2 Other Sources of Highway Flying Rock

The major source of flying rocks in winter is the sand used in enhancing highway traction for the sake of highway safety. However, in seasons other than the winter, the major source is construction and landscape debris. The Colorado Department of Transportation has been using rocks with a grain size smaller than 3/8 of an inch, while a good portion of rocks on highways have a grain size larger than the maximum size used in highway sanding. It is interesting to note that larger rocks cause more severe damage to auto windshields. Thus, to minimize windshield damage, some effort must be devoted to the minimization of the construction and landscape debris on highways.

1.1.3 Impact of Sanding

The direct impact of the shift in winter roadway maintenance is beneficial to both the traveling public in terms of highway safety and reduction of insurance expense and the general public in terms of the improvement of air quality. Traditionally, the sand-salt mixture was used to enhance highway traction in the winter. This winter sanding of roadways has caused serious environmental, health and economic impacts. This study is devoted to the study of the economic impact to CDOT, the insurance industry and the general public. In other words, it examines the economic impact in terms of the cost to CDOT in its efforts to maintain safe roadways in winter and the cost to the traveling public due to the resulting damage to cars. Even then, the cost issues in sanding are multiple; the study addresses only those directly related to the application and removal of sand and the windshield damage resulting from flying rocks. The CDOT Maintenance Division has estimated that it spends as much as one third of its maintenance budget on snow and ice control. The CDOT cost issues are addressed in Chapters 2 and 3 of this report.

In terms of CDOT maintenance cost, the Maintenance Division has kept excellent annual cost and budget records, which are the base of the cost of sanding study. The auto insurance industry in Colorado provided the cost statistics for the windshield damage. The study was extended to cover the rock airborne mechanism using finite element analysis and road tests with a high-speed camera, and the effect of rock size and shape on windshield damage severity using the slingshot with a high-speed camera to record the test.

A research project on "Environmentally Sensitive Sanding and Deicing Practices" was carried out by the Center for Geotechnical Engineering Science under the sponsorship of the Colorado Department of Transportation. The study recommended a shift in the CDOT winter highway maintenance from the heavy use of sand-salt mixture to the coordinated use of sand and deicing chemicals for the purpose of reducing airborne particulate matter with a particle size smaller than 10 microns, called PM 10. The implementation of the research findings has led to the reduction of PM 10 problems and auto windshield damage from flying rocks, and the enhancement of air quality.

1.1.4 Cost of Sanding

The sanding cost includes (by the sequence of their occurrence):

- Acquisition sand.
- Storage and mixing of sand and salt or other deicing chemicals
- Placement of sand on roadways.
- Snow, ice and sand removal from highways (to implement the **bare pavement always** policy), guardrail locations and drainage ditches after snow melt.
- Use of alternate granular materials.
- Pavement wear and tear.
- Accelerated paint stripe deterioration.
- Disposal/recycling of sand. Recycling involves the removal of fine particulates.

In principal, each of the above-mentioned costs constitutes a part of the total cost of sanding and should be delineated. However, after examining the CDOT cost record, it was found the above cost items are too refined to accurately account for. Thus, the sanding cost is based on the available CDOT cost records. The records from as far back as the early 90's are closely examined. This study yields the cost information critical to the formulation of an optimal winter highway maintenance strategy in Colorado.

1.1.5 Cost of Windshield Damage

“Zero sand” constitutes the most ideal condition for minimizing the cost to the traveling public. With the absence of loose sand, the windshield damage and the loose sand related vehicle collision after snowmelt are avoided. Since the complete elimination of sand is not likely, the following issues and the associated cost will also have to be addressed: the optimal amount of sand application, the choice of grain size and grain shape to maximize highway safety and minimize the cost to the traveling public, and the optimal sand removal timing.

Vehicles kick up sand particles and cause them to become airborne when accelerating and/or cruising. Subsequently, the particles could collide with a trailing vehicle and cause damage. To observe the particle airborne mechanism, a Kodak high-speed camera was used during the field tests. The particle airborne mechanism was recorded in the Kodak H-S camera at a very high speed of 1,000 frames per second. Finite element analyses were then performed to simulate the mechanism. The analysis confirms the particle movement in the near vertical direction during vehicle cruising.

Due to the nature of rock-windshield impact, its damage comes in many different forms. The damage pattern and the shape of each indentation are surveyed. The survey was carried out in both Denver and Greeley to detect any potential difference in damage characteristics between the urban and rural areas. The rock-windshield impact tests were performed to investigate the effect of the shape, type, weight, and size of rocks on the indentation pattern and severity. A slingshot was calibrated for its extension and resulting velocity as a function of rock mass and then used in the test to provide the momentum for rock particles and the Kodak H-S camera was used to record the motion. The recorded image was subsequently used in calculating the rock particle velocity.

The major interest of the motor vehicle insurance industry lies in the minimization of the cost to insurers. Since the “zero sand” condition is most ideal and yet impractical, it is important to formulate an optimal winter highway maintenance practice and policy that minimizes the insurance cost. The results of this study will aid in such a formulation effort.

1.1.6 CDOT Winter Highway Maintenance Practice vs Windshield Damage

The rock-windshield impact results in windshield damage. The Colorado auto insurance industry provided the cost information of insurance claims that reflects the cost to the industry and its customers. It is obvious that more rocks on the highway cause more damage to vehicles. In the past decade, there has been a gradual reduction in use of sand on Colorado highways, particularly since 1994, which is reflected in the increased use of deicing chemicals. It is very interesting to note that the claim records actually reflect a strong correlation to the gradual shift in the CDOT winter highway maintenance practice of decreasing use of sand-salt mixture and increasing use of deicing chemicals.

1.2 Objectives of the Study

The objectives of this study are to study: 1) all aspects of the cost associated with the CDOT's winter roadway maintenance, including materials, labor and equipment; 2) the historical shift of the CDOT winter highway maintenance from the heavy use of sand to the emphasis in using deicing chemicals; 3) the airborne and impact mechanism of highway rocks; 4) the effect of rock type, size and shape on auto windshield damage; 5) the correlation between the reduced use of sand and the increased use of deicing chemicals on the insurance cost. The study results, when implemented, should assist the Maintenance Division to justify the reduction in the use of sand as a winter highway traction enhancement agent, to increase the use of deicing chemicals and to develop and maintain a cost-effective winter maintenance program involving the coordinated use of sand and deicing chemicals to enhance safe passage for motorists in the winter months, while reducing the insurance cost to our traveling motorists.

1.3 Background and Significance of this Study

The CDOT Research Branch conducted interviews with the Department Maintenance personnel after the study was presented at the Research Implementation Council. During these interviews, cost items associated with the winter street sanding were identified. Meetings were also held between the CDOT Research Branch personnel and representatives from the insurance industry to identify the industry concerns on the effect of street sanding on the insurance cost. Thus, this study addresses issues of concern to CDOT, the insurance industry and the traveling public, including cost of sanding to CDOT, cost of sanding to the insurance industry and the traveling public, and the impact of the shift in CDOT winter highway maintenance practice on auto safety and the associated vehicle repair cost. Research results, when implemented, can help CDOT formulate a winter highway maintenance strategy and policy that not only enhances highway safety and is cost-effective for CDOT, but also reduces the vehicle damage repair cost to the traveling public.

1.4 Expected Benefits of Study

To implement the **Bare Pavement Always** policy to provide safe passage for traveling motorists in winter months, the Colorado Department of Transportation spends as much of 1/3 of its maintenance budget on snow and ice control and the motor vehicle insurance industry spends in excess of 30 million dollars annually in Colorado to pay the insurance claims pertaining to windshield damage. It is expected that the implementation of these study results will contribute to the formulation of a winter highway maintenance strategy and policy that is cost-effective to all parties of concern: the Colorado Department of Transportation, the traveling public, and the motor vehicle insurance industry.

1.5 Research Approach

The CDOT cost of sanding, the windshield damage cost of sanding, the particle airborne and rock-windshield impact mechanism, the effect of rock type, and grain size and shape on windshield damage severity and patterns are the four emphases of this research. Examining and analyzing the CDOT winter highway maintenance and annual cost records addressed the CDOT aspect of sanding cost. The analysis of the insurance cost statistics shed light in the insurance aspect of sanding cost. The laboratory and field tests were performed to understand the rock airborne and rock-windshield impact mechanism. A Kodak high-speed camera was used to record all field tests for the purpose of using the recorded image to back calculate the rock impact velocity and windshield fracture patterns and mechanism. Laboratory tests were performed to characterize the density, shape and size of rocks used in the impact tests. The rock characteristics were later related to the windshield damage patterns and severity.

2. Cost of Sanding Colorado Roadways

2.1 Introduction

In this section, we analyze the cost involved in keeping Colorado roadways clear from snow and ice. The Colorado Department of Transportation requested The Center for Geotechnical Engineering Science at the University of Colorado at Denver to investigate the true cost associated with sanding and snow removal. Using the maintenance cost data base made available by Ed Fink and Susan McOllough at CDOT Maintenance in Golden, a spreadsheet of cost information was created, which allowed the compilation of the detailed analysis of the direct and indirect costs of keeping Colorado roadways clear and enforcing the Colorado "Bare Pavement Always" policy. The spreadsheet is available as Appendix A, and pertinent data are presented graphically. In this section an in-depth study of the maintenance costs for each of the nine maintenance sections of Colorado is performed, then all data are combined to create a profile based on costs and snowfall in Colorado from the years 1993 to 2000. When possible, costs are normalized to units on a per lane mile basis. This allows the comparison of areas with little snowfall to the areas with large amounts. Section 2.2 investigates the cost components for each section, including sand and liquid chemical deicer costs, labor costs, and equipment costs. These categories were chosen to best illustrate the different practices among the different regions, and allow a basis for defining maintenance needs through demographic location, material sources, and economics. Section 2.3 examines the statewide overall costs and relates them to annual snowfall, while Section 2.4 examines the policy shift from strictly sand-rock salt mix before the early 90's to the contemporary heavy use of chemical deicers.

2.2 Sectional Costs Related to Sanding Our Roadways

Costs of materials, labor and equipment associated with each maintenance section are examined. A maintenance cost database was created from the CDOT maintenance ledger books, and analyzed to give an overall cost picture of Colorado winter roadway maintenance practices. The CDOT maintenance sections in Colorado are as follows: 1) Greeley; 2) Grand Junction; 3) Durango; 4) Pueblo; 5) Aurora; 6) Craig; 7) Alamosa; 8) Denver; and 9) Eisenhower Tunnel. Some costs reflect the cost increases, partially due to inflation. The reader should be aware that the cost data provided by CDOT are only for estimation purposes and should not be considered as absolute costs.

2.2.1 CDOT Maintenance Activity Codes Tracked

Fee Code	Item	Units
Materials		
7	Sand	Tons
17	Salt	Tons
54	Sand and Salt mixture	Tons
69	Liquid Deicer	Gallons
70	Solid Deicer compounds	Tons
71	Other Deicer compounds	Tons
Equipment and Labor		
220	Sweeping Mechanical	Mile
222	Sweeping Manual	Hours
402	Snow Removal / Sanding	Mile
403	Ice Control	Hours
406	Snow removal Spec. Equip.	Hours

2.2.2 Materials Cost per Section

Greeley Figure 2.2.2 illustrates the annual material cost per lane mile in the Greeley region for an eight-year period. Notice the drastic reduction in cost from 1992 through 1993. This reduction in sand cost caused the total material cost to decline also. In 1996 however, the total cost increased due to a market shift. This increase is evidenced by the increasing cost of sand-salt mixture. By 1998 the cost of the individual materials of sand and salt approached zero. At this same time the price of sand-salt premix was increased. Liquid deicer was introduced for use in the region on 1997. The use of liquid has steadily increased, Figure 2.2.3. The use of liquid deicer will be further examined in Section 2.6.

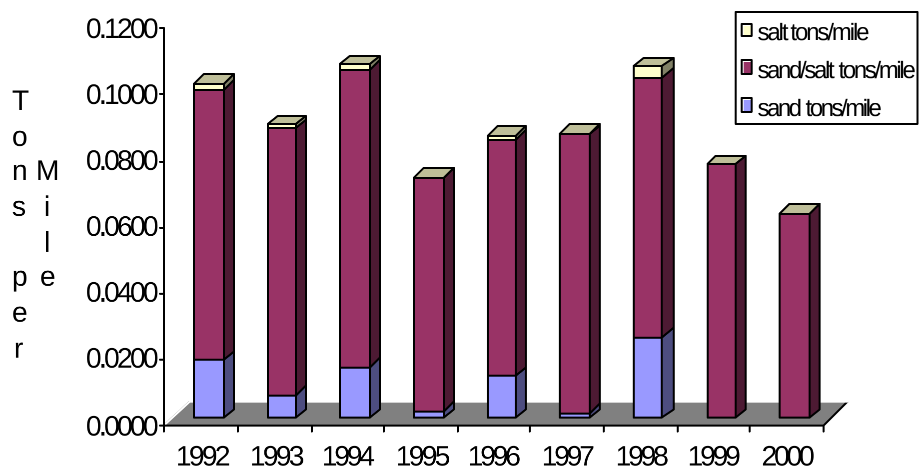


Fig. 2.2.1 Solids Use for Greeley Region

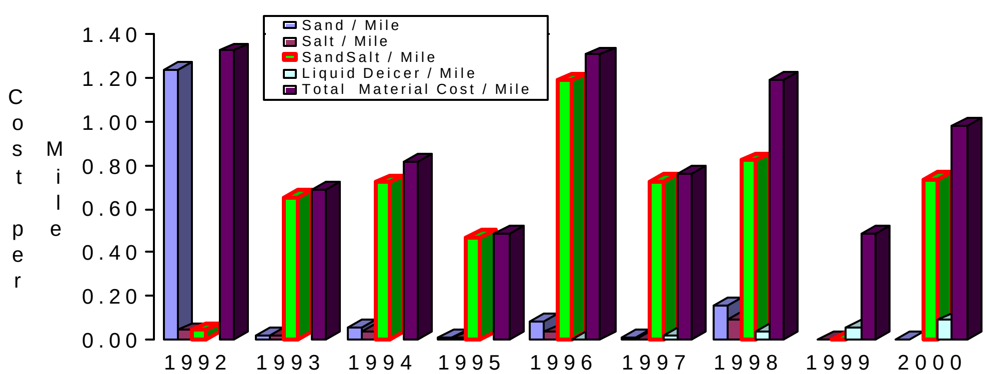


Fig. 2.2.2 Material Cost per Mile Greeley Region

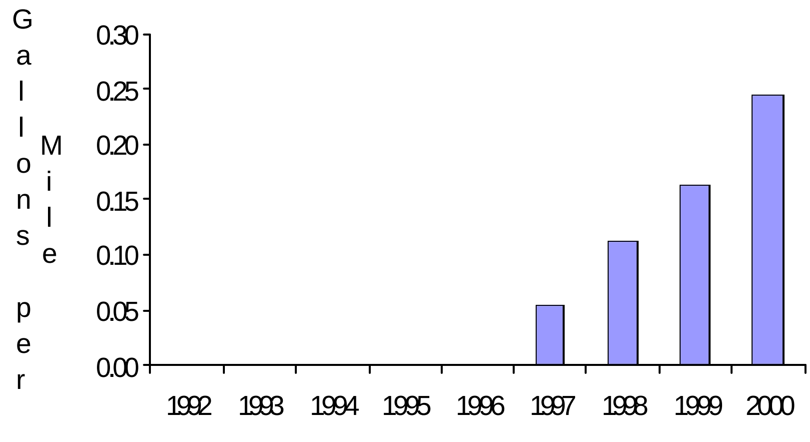


Fig. 2.2.3 Liquid Deicer Use per Mile Greeley Region

Grand Junction In the Grand Junction region chemicals were in use as early as 1993, Figure 2.2.6. The steady annual increase is an indication of their popularity. Data for 1995 is unavailable, but one can assume that chemical deicer was used. Sand was completely eliminated from the inventory in 1993 and Grand Junction has steadily decreased its use of sand. A record low of only 0.009 tons per lane mile was recorded in 1998. There is an increase of cost totals, which relates to the use of liquid deicer. Sand use remains steady throughout this same period.

Table 2.4 Solids Use per Mile Grand Junction

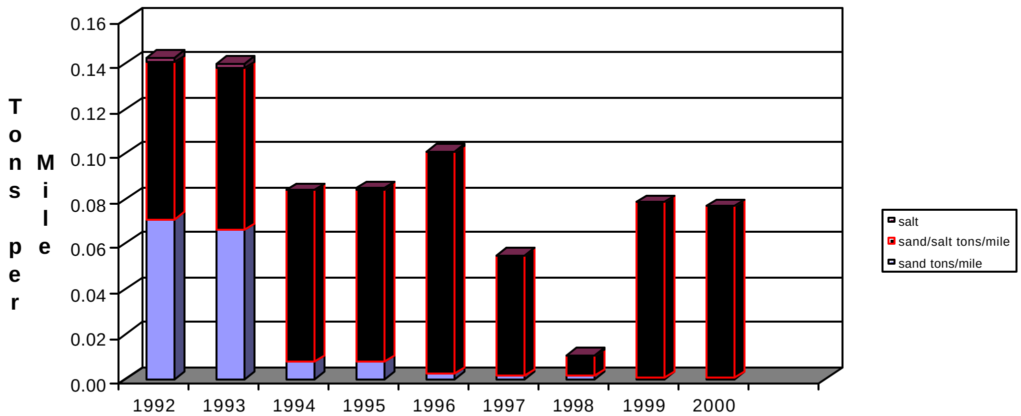


Figure 2.2.4 Solids Use per Mile

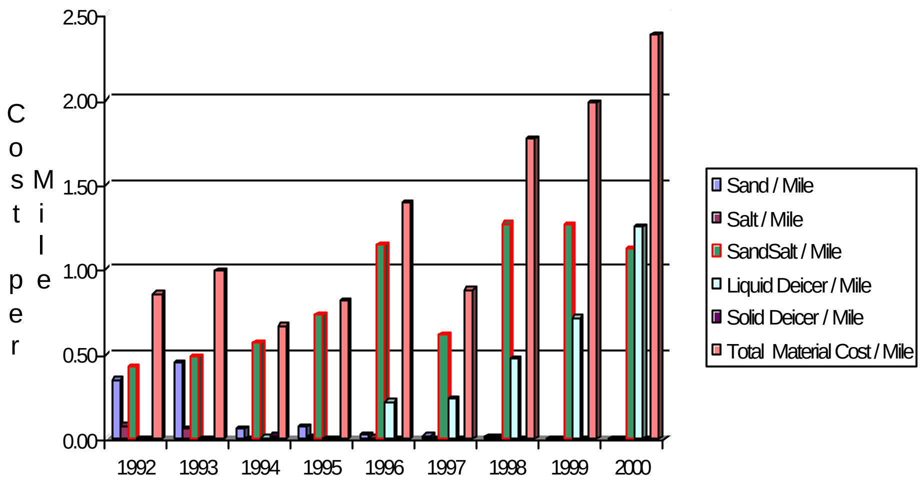


Figure 2.2.5 Materials Cost per mile

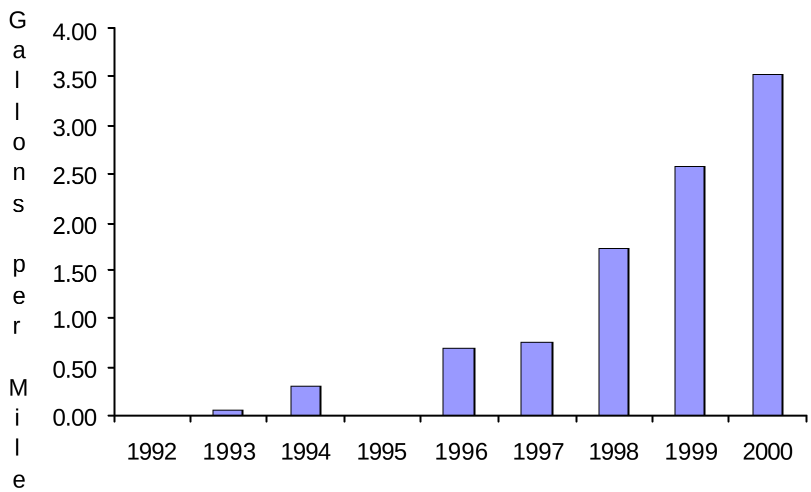


Fig. 2.2.6 Liquid Deicer Use per Mile Grand Junction Region

Durango In the Durango region sand was used exclusively up until the year 1998, when two different forms of chemical deicers were introduced. The solid form is more expensive than the liquid form. In Durango, the primary sanding material is the local rock. With heavy snowfall, the demand for sanding is high. Although deicing chemicals were introduced in 1997, the increase in use has been slow. A large amount of solid deicer was used in the year 2000, whereas in the three years prior, liquid deicer was preferred. The use of liquid deicer was minimal. Data illustrates that liquid deicer use in 2000 amounted to only 1½ gallon per lane mile, Figure 2.2.9.

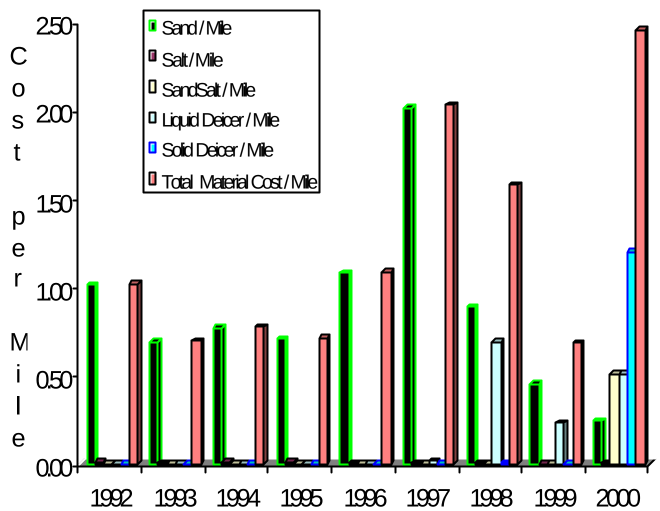


Fig. 2.2.7 Material Cost per Mile Durango Region

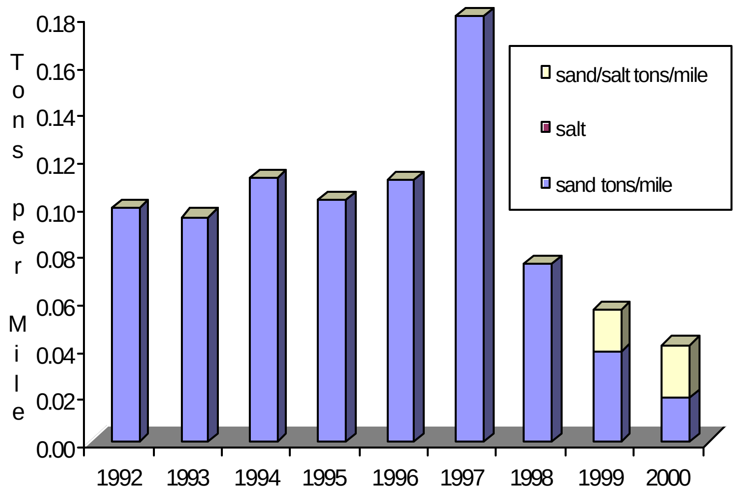


Fig. 2.2.8 Solids Use per Mile Durango Region

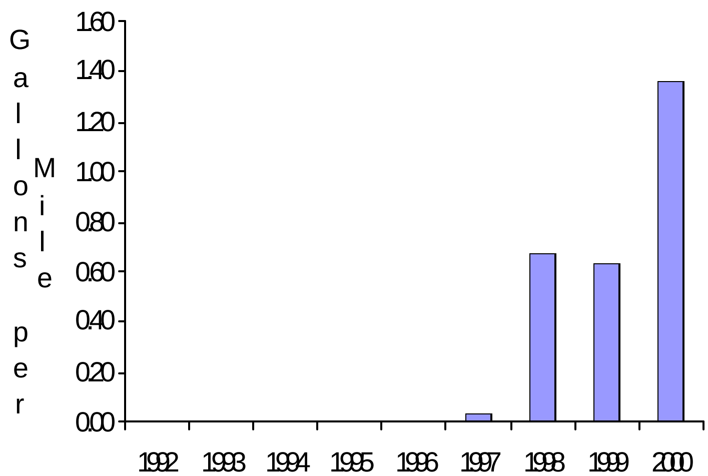


Fig. 2.2.9 Liquid Deicer Use per Mile Durango Region

Pueblo The Pueblo region maintained a steady material cost from 1992 through 1998. In 1999 however, it incurred a drastic cost increase. This increase happened around the same time that a large amount of sand-salt mixtures was used. 1994 was another year when a large amount of sand-salt mixes was used. This indicated the possibility of heavy snowfall in those two years. However, it did not reflect in the cost increase for 1994. The sand/salt mix could have been much cheaper in 1994 than 1999.

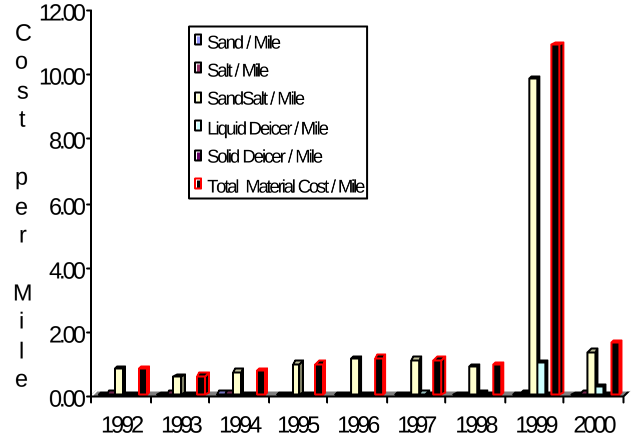


Fig. 2.2.10 Material Cost per Mile Pueblo Region

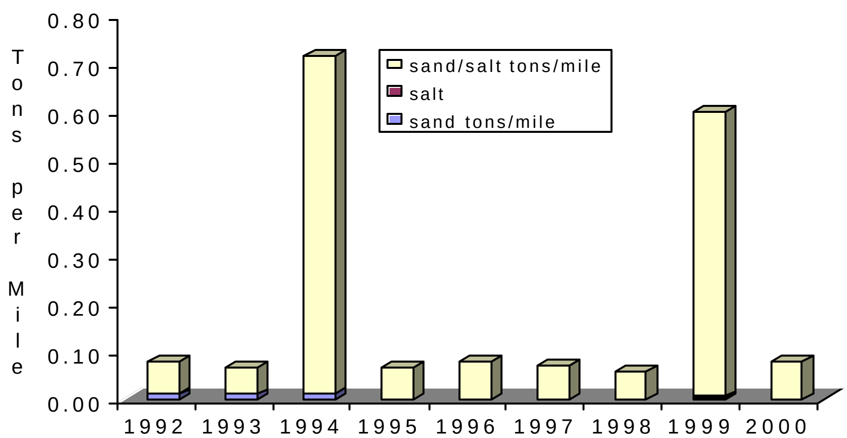


Fig. 2.2.11 Pueblo Region Solids Use per Mile

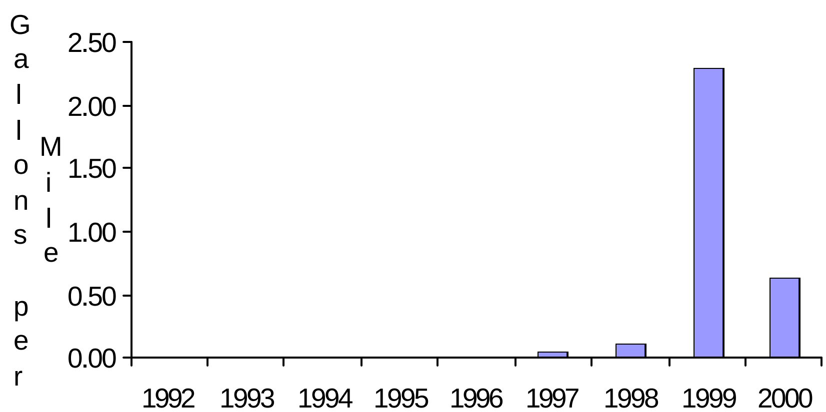


Fig. 2.2.12 Pueblo Region Liquid Use per Mile

Aurora The Aurora region has initiated a significant use of liquid deicers since 1997. Prior to this, the use of sand-salt mix was predominant. In fact, in 1997 about 90 % of material cost was attributed to sand-salt mix. From 1997 to 2000, cost ratios differed, while the combined material cost per lane mile remained fairly constant. Figure 2.2.14 shows an application rate of 0.15 tons of sand-salt mix per lane mile from 1993 through 1996. In 1997 the sand-salt use dropped to 0.13 tons per mile. This large quantity of sand-salt mix use may be due to the practice of "full length" sanding instead of sanding only the strategic locations. The Aurora region, on average, used 1.0 gallon of liquid deicer per lane mile, which amounts to about one fourth of the application rate of Grand Junction in the year 2000.

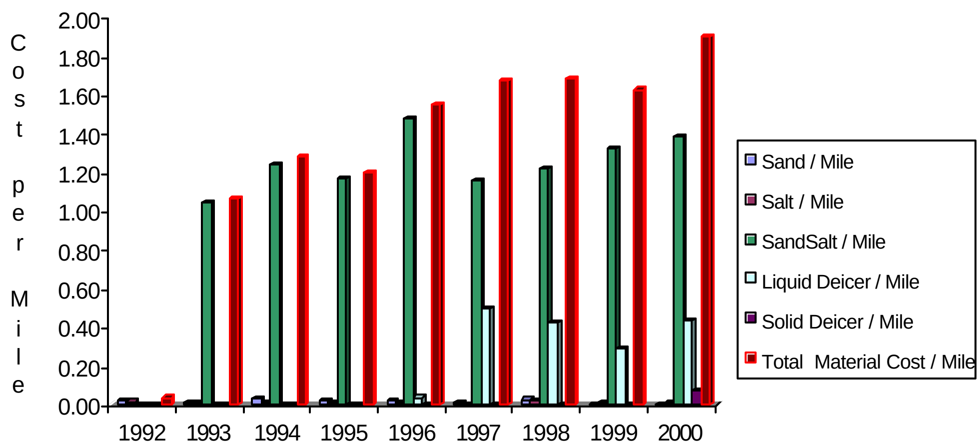


Fig. 2.2.13 Material Cost per Mile Aurora Region

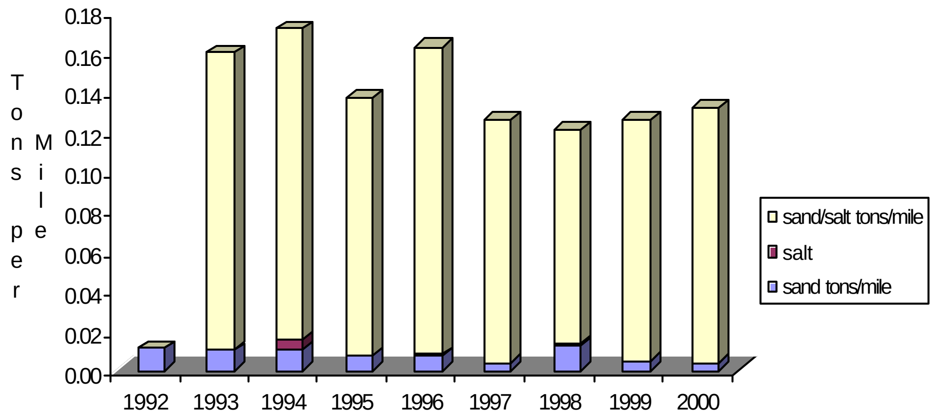


Fig. 2.2.14 Solids Use per Mile Aurora Region

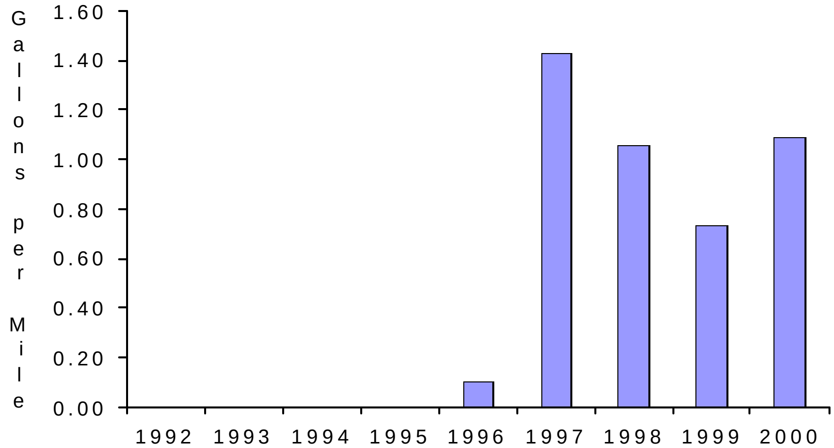


Fig. 2.2.15 Liquid Deicer Use per Mile Aurora Region

Craig The material cost increased almost linearly as shown in Figure 2.2.16. The sand-salt mix is the dominating material in this region. The total material cost remained nearly constant during the 8-year period. This could be the result of decreasing use of sand or its unit price had not increased over the same period. The cost spread between sand-salt mix and sand began to increase after 1996. This indicated the acceptance of sand-salt mixture as the material of choice in the Craig region. Figure 2.2.16 indicated that money was spent on sand, as an independent material in 1993. However, no indication of sand use in the same year is shown in Figure 2.2.17. Thus, the 1993 data was discarded as unreliable information.

Figure 2.2.18 indicates the initiation of the liquid deicer use in 1999. The liquids have been used for only a short time, so it is difficult to estimate the cost impact of liquid use in the region.

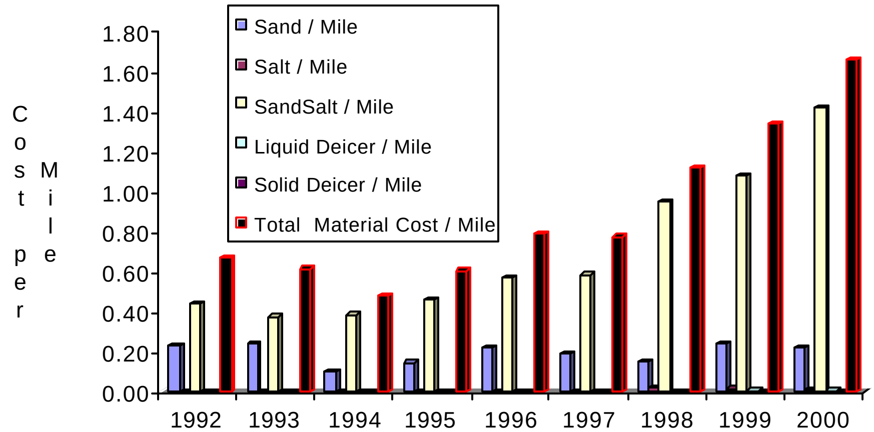


Fig. 2.2.16 Material Cost per Mile Craig Region

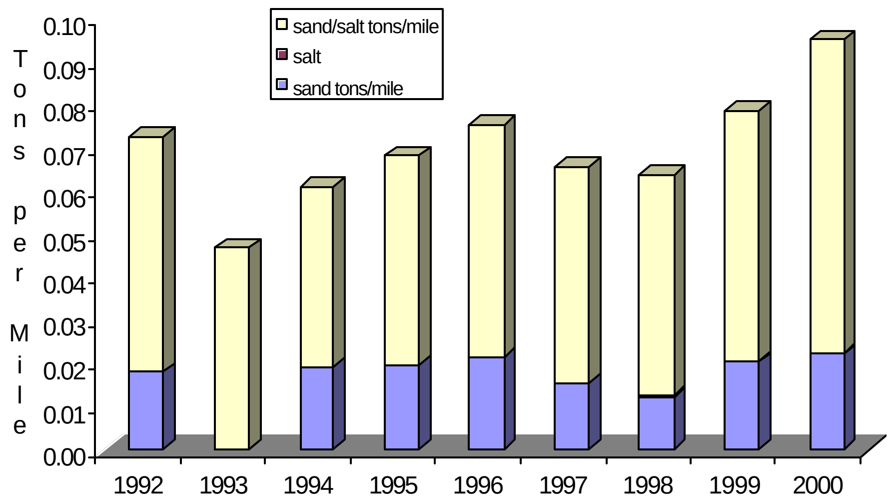


Fig. 2.2.17 Solids Use per Mile Craig Region

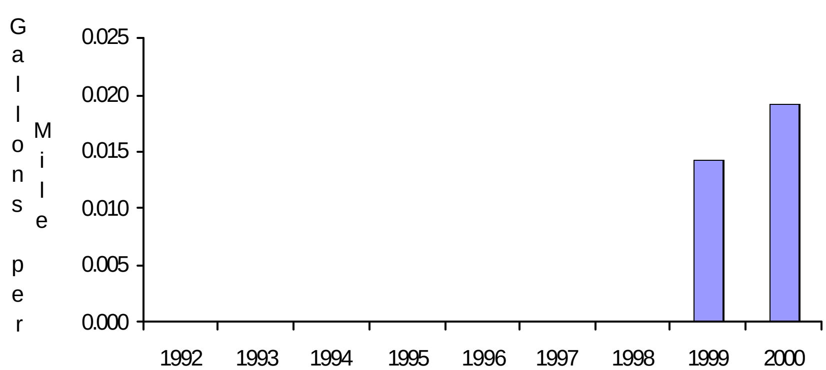


Fig. 2.2.18 Liquid Deicer Use per Mile Craig Region

Alamosa The Alamosa region did not use liquid deicers till 2000 and the application rate was 0.25 gallons per lane mile as shown in Figure 2.2.21. Figure 2.2.19 indicates this region historically uses sand and salt as independent materials or as mixtures. In the year 2000, a very low amount of sand and salt as independent materials was used and the mixtures accounted for about 95% of the total application. The region traditionally uses conservative amounts of sanding materials, except for 1995. The general trend shows that sand-salt mixture quantity is twice that of sand alone.

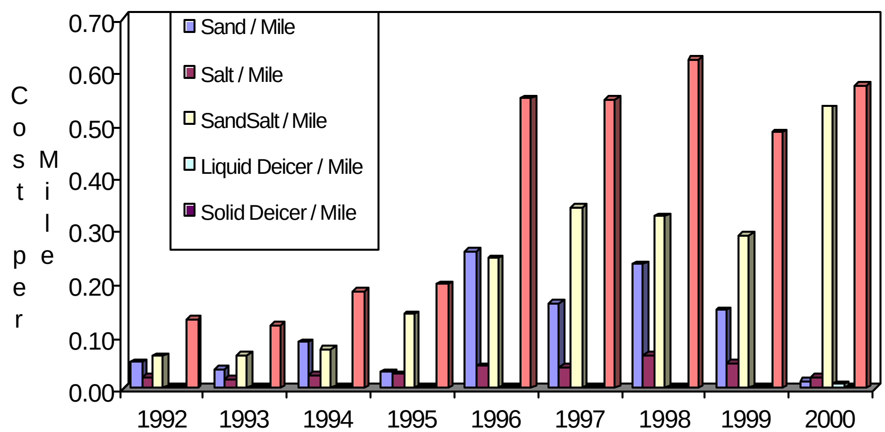


Fig. 2.2.19 Material Cost per Mile Alamosa Region

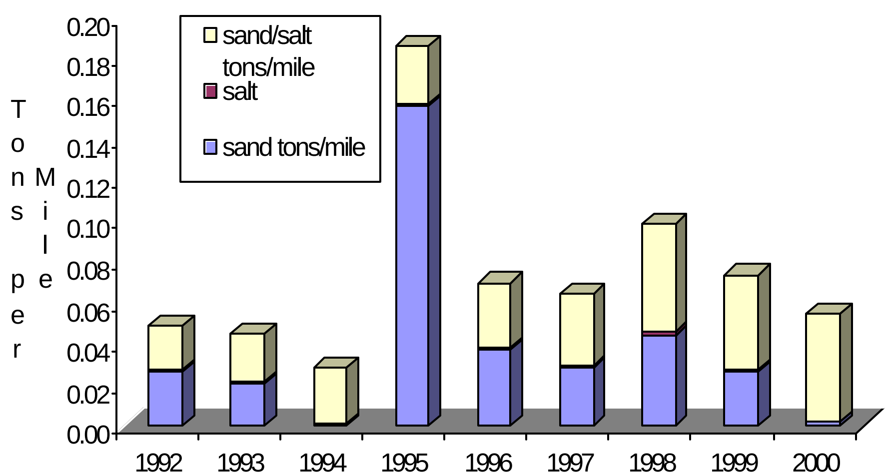


Fig. 2.2.20 Solids Use per Mile Alamosa Region

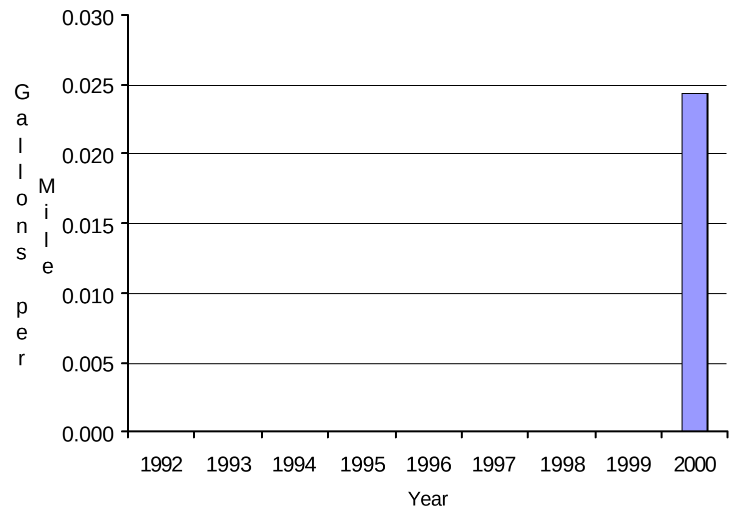


Fig. 2.2.21 Liquid Deicer Use per Mile Alamosa Region

Denver The cost for materials other than sand-salt mixtures was introduced in 1994. At the introduction of chemical deicers, the solid form was preferred over the liquid form till 1997 when the trend was reversed and the liquid deicer became the material of choice. The cost for the sand-salt mixture remained relatively constant over the last eight years. The total cost per lane mile has continued to increase similar to that of the other regions because of inflation as shown in Figure 2.2.22. The application rate of the sand-salt mix was reduced by nearly one half over the eight-year period from 0.18 in 1993 to 0.10 tons per lane mile in 2000 as shown in Figure 2.2.23. The liquid deicer use has increased exponentially since its introduction in 1994. Nearly five gallons per lane mile were recorded in 2000.

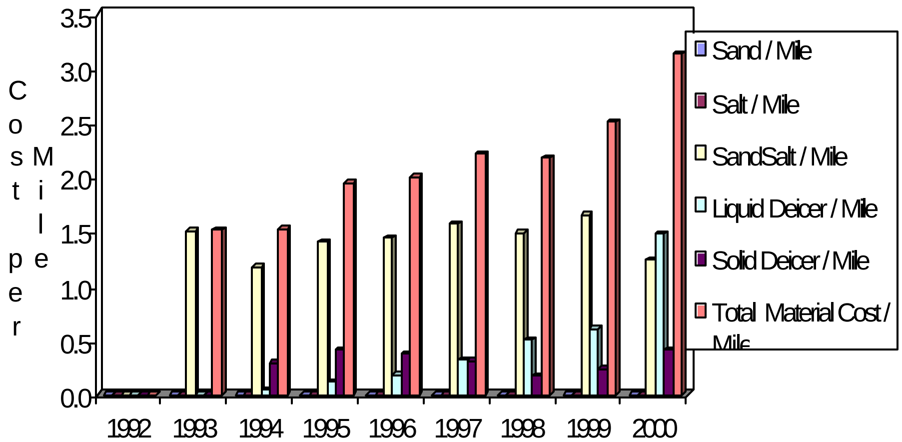


Fig. 2.2.22 Material Cost per Mile Denver Region

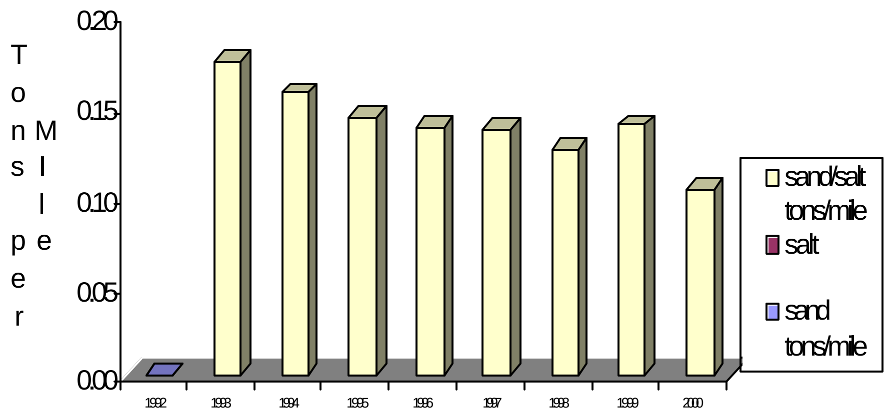


Fig. 2.2.23 Solids Use per Mile Denver Region

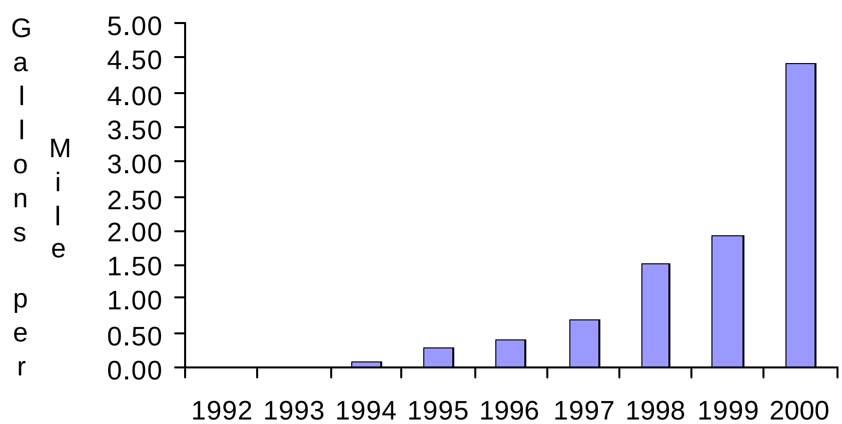


Fig. 2.2.24 Liquid Deicer Use per Mile Denver Region

Eisenhower Tunnel Data were available only from 1992 to 1994. The data show that only rock salt was used during this period. The overall cost per lane mile ranges from $50 to $70 at an application rate of 0.8 to 1.4 tons per mile. Because of its inconsistency, the data was not entered into the statewide statistics. The average cost for all other regions in the state is approximately one dollar per lane mile.

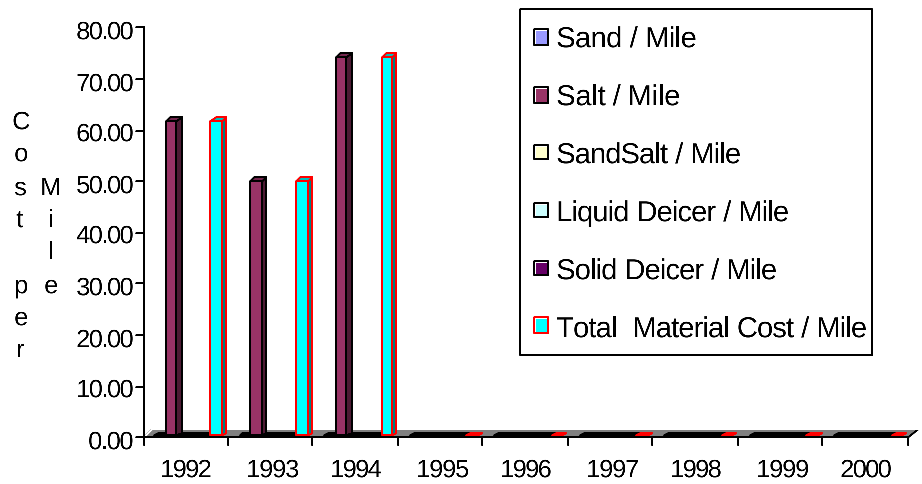


Fig. 2.2.25 Material Cost per Mile EisenhowerTunnel Region

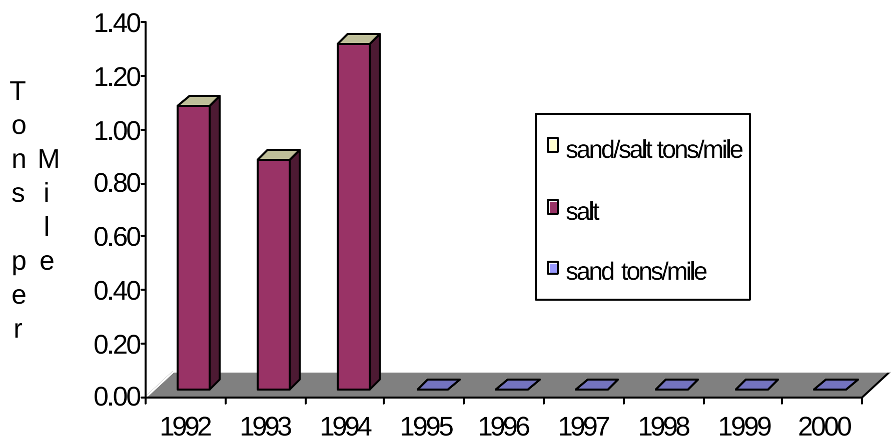


Fig. 2.2.26 Solids Use per Mile Eisenhower Tunnel Region

2.2.3 Labor Cost

In charting the labor cost for each section, the following cost factors were included: sand sweeping, snow removal, sanding, and ice control with the largest expense being the snow removal and sanding, which account for over 95% of the labor cost. This section deals only with the labor cost.

Greeley Figure 2.2.27 shows that the labor cost increase reflects the increase in the cost of living. On a per lane mile basis, the labor cost increases from about $0.90 in 1992 to $1.35 per lane mile in 2000.

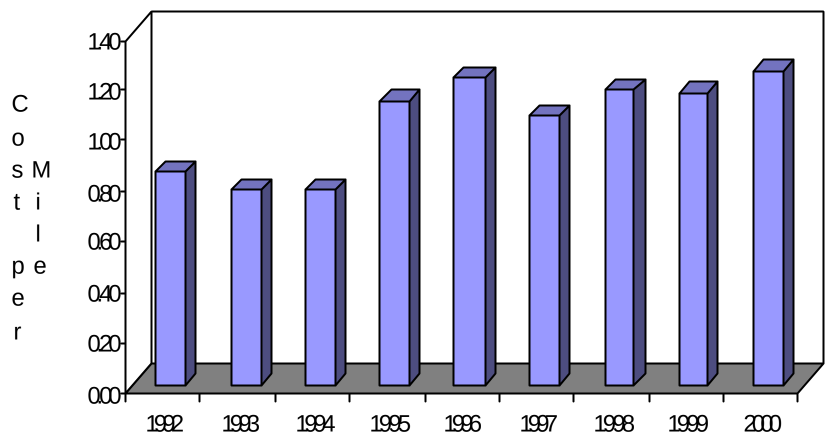


Fig. 2.2.27 Labor Cost per Mile Greeley Region

Grand Junction In 1997 and 1998, the Grand Junction region experienced a decrease in personnel cost, which coincided with a reduction in solid material use in the same period. This was possibly due to the low snowfall and/or the reduction in the cleanup personnel cost due to the aggressive use of liquid deicing chemicals as shown in Figure 2.2.28.

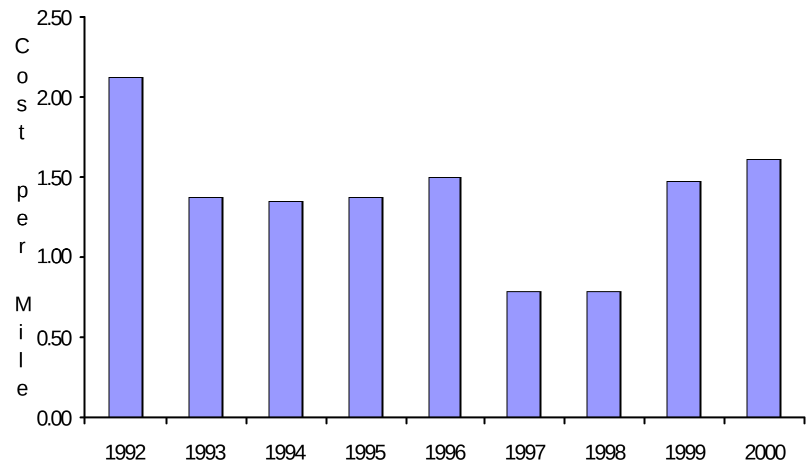


Fig. 2.2.28 Personnel Cost per Mile Grand Junction Region

Durango The annual labor cost in the Durango region is quite an irregular pattern, Figure 2.2.29. Before the introduction of liquid deicer, the labor cost was decreasing for a period of four years. Once the liquid deicer was introduced, the labor cost increased significantly. Could this labor cost increase be caused by the training cost required during the transition time?

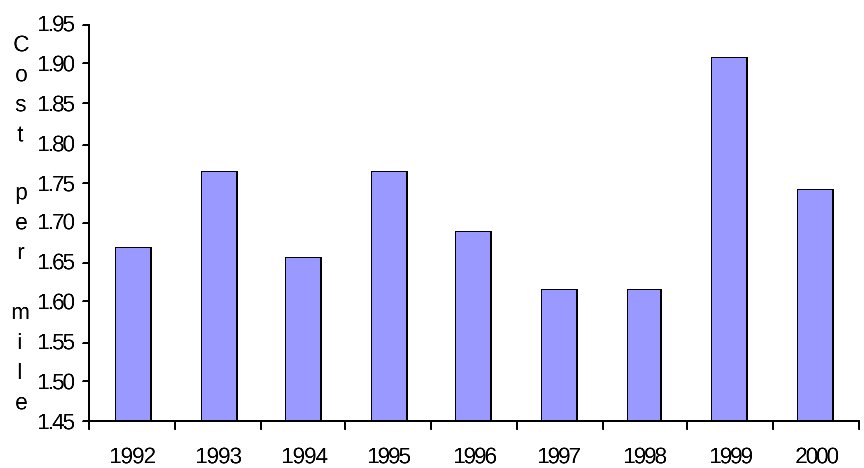


Fig. 2.2.29 Personnel Cost per Mile Durango Region

Pueblo The labor cost in the Pueblo region, Figure 2.2.30, has remained amazingly constant over the study period, except for 1999. Since the spike in labor cost coincided with the spike in materials cost for 1999, the heavy snowfall could be responsible for the instant cost increase and then decrease.

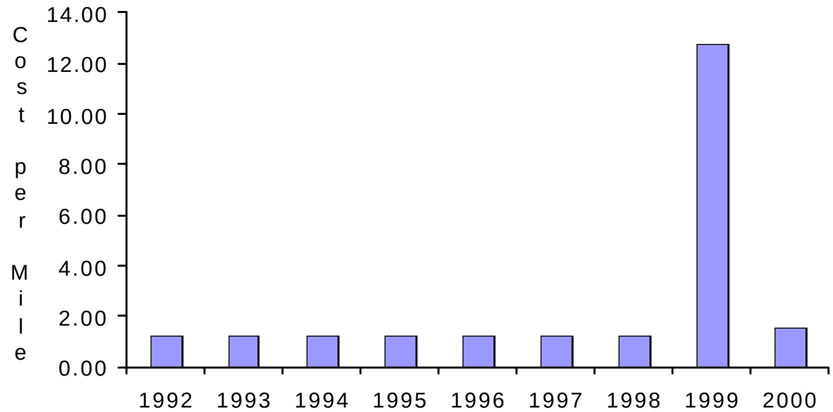


Fig. 2.2.30 Personnel Cost per Mile Pueblo Region

Aurora The region experienced a small labor cost increase to an otherwise stable labor cost when the liquid deicers were introduced in 1997 and 1998 as shown in Figure 2.2.31. The labor cost pattern is similar to that of the Pueblo region.

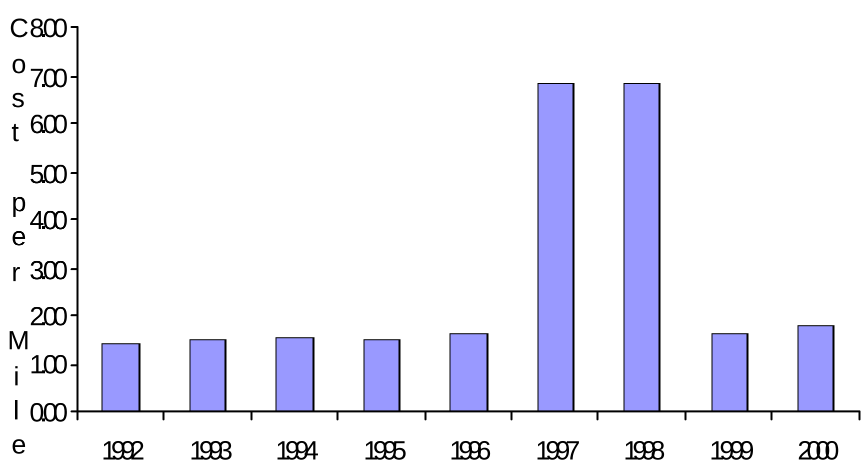


Fig. 2.2.31 Personnel Cost per Mile Aurora Region

Craig Figure 2.2.32 shows that as the materials cost rose, the labor cost rose with it at the same rate. This suggests labor costs are more likely weather driven than inflationary.

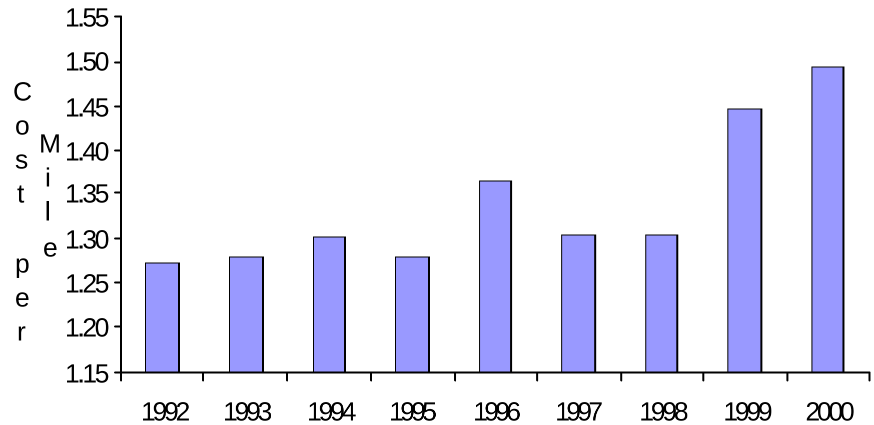


Fig. 2.2.32 Personnel Cost per Mile Craig Region

Alamosa Figure 2.2.33 shows that the labor cost for the Alamosa region increased with materials cost as indicated in Figure 2.2.19. So this increase could be weather driven.

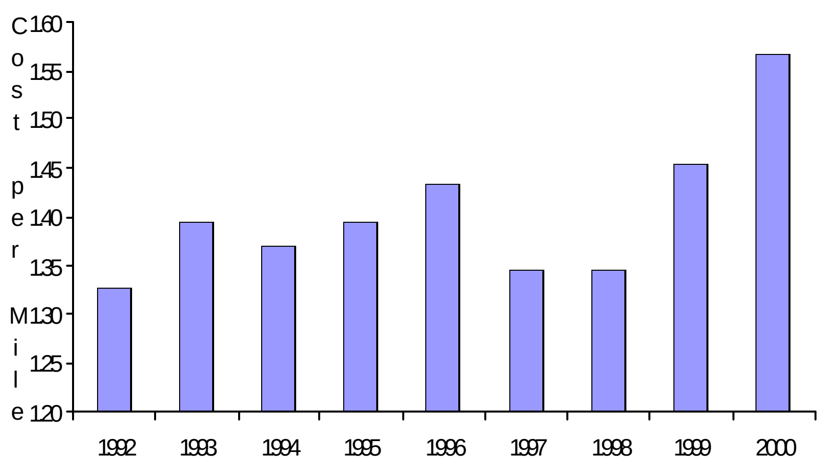


Fig. 2.2.33 Personnel Cost per Mile Alamosa Region

Denver The labor cost in the Denver region has experienced little variation over the study as shown in Figure 2.2.34. Mild winters during this time might explain this steady trend.

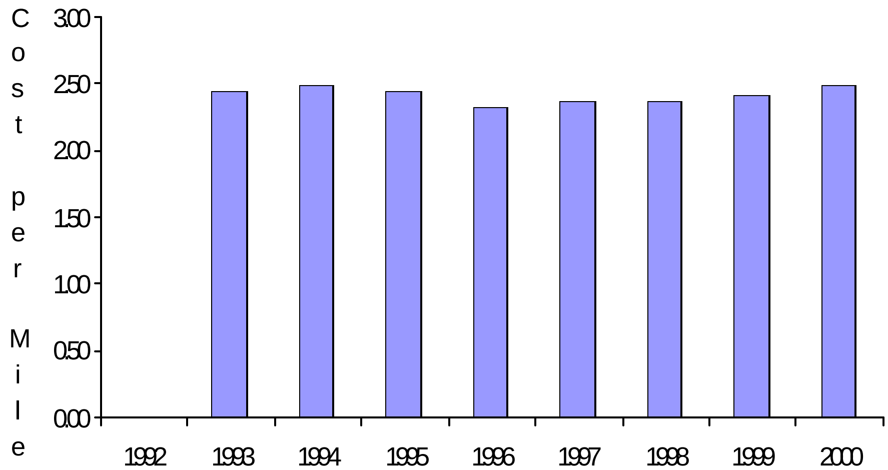


Fig. 2.2.34 Personnel Cost per Mile Denver Region

Eisenhower Tunnel The labor cost has increased steadily over the study period. No material cost was available for most of the eight-year study period. Besides, the labor cost data was also missing for 1999, as shown in Figure 2.2.35. The labor cost per lane mile is the most expensive among all regions in the state. This could be due to the safety concerns for the ski traveling public peculiar to this steep roadway.

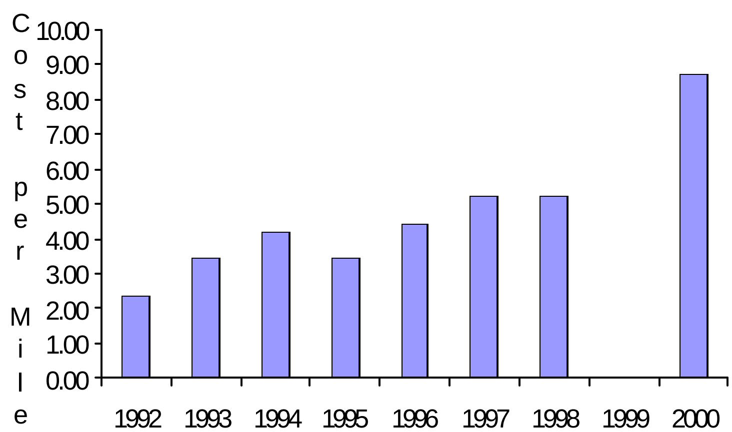


Fig. 2.2.35 Personnel Cost per Mile Eisenhower Tunnel Region

2.2.4 Equipment Cost Per Section

The equipment cost per section was studied using the same fee codes used in labor calculations, since the materials codes do not have equipment cost associated with them. There is no breakdown between sanding equipment and chemical deicing equipment. The equipment breakdowns are: manual sweeping, mechanical sweeping, snow removal and sanding, ice control, and special equipment for snow removal. Since the portion of equipment cost for snow removal special equipment is negligible, the cost of equipment for liquid deicer application is merged with snow removal and sanding fee code 402 in CDOT field manual for maintenance management system. It may be worthwhile for CDOT to add a cost code for liquid deicing application to better track its expense.

Greeley There was a large increase in equipment cost per mile in 1996, Figure 2.2.36, which was the first year that the Greeley region started to use liquid deicers. It is noted that, as application of liquid deicer increased in subsequent years, the equipment cost remained unchanged. The cost offset is caused by the steady decrease in solids use per mile in Greeley. While it is more expensive for equipment per mile with the use of liquid, this cost increase is offset by the reduction in the cost of materials and sand sweeping labor. This suggests that the use of liquid deicers is more cost-effective.

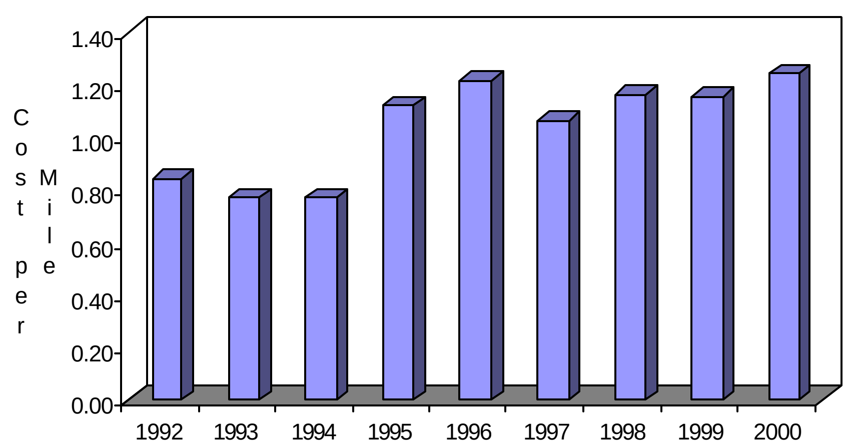


Fig. 2.2.36 Equipment Cost per Mile Greeley Region

Grand Junction The equipment cost for Grand Junction for 1997 is not available. Figure 2.2.37 shows a steady increase in equipment cost. Grand Junction was also one of the sections aggressively promoting the use of deicing chemicals. The steady rise suggests that the equipment cost increase is mostly inflationary.

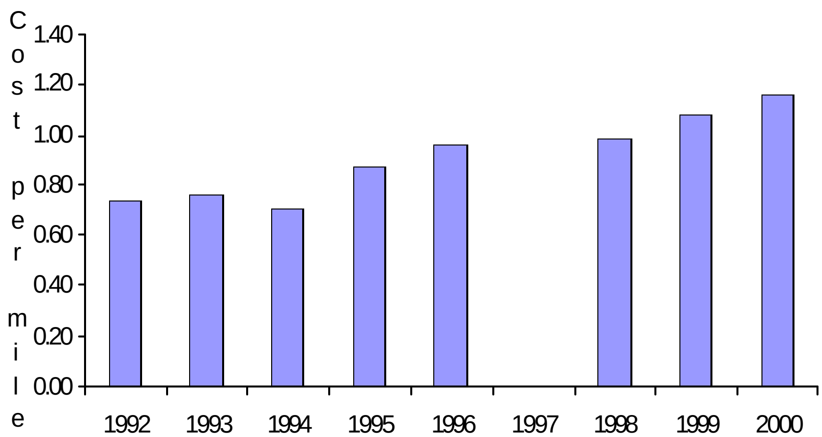


Fig. 2.2.37 Equipment Cost per Mile Grand Junction Region

Durango Durango was one of the last regions to begin using liquid deicer. The Durango regional cost for equipment use is high in the early years covered in this study. Figure 2.2.38 shows that there was some increase in the equipment cost when the liquid deicer was introduced in 1998.

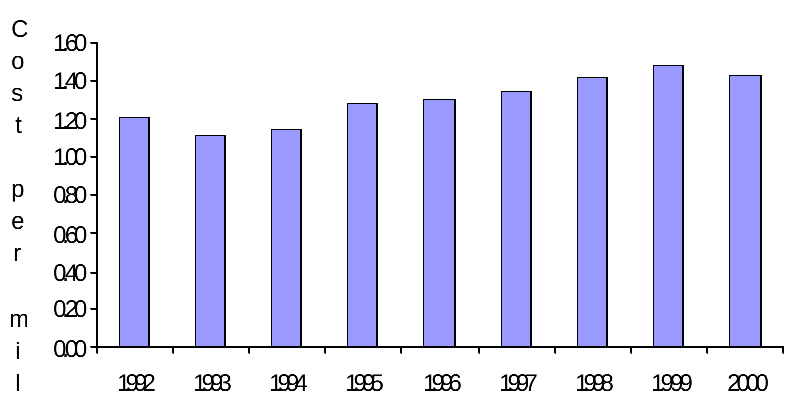


Fig. 2.2.38 Equipment Cost per Mile Durango Region

Pueblo The Pueblo region equipment cost closely follows its materials cost. A sharp cost spike shows up in all cost data for Pueblo in 1999 including the equipment cost in Figure 2.2.39. This is most likely associated with several large snowstorms in the Pueblo region in the year. Otherwise, the equipment cost, in general, has been very stable. Data from the Pueblo region shows that the equipment cost remained low compared to the 1999 cost.

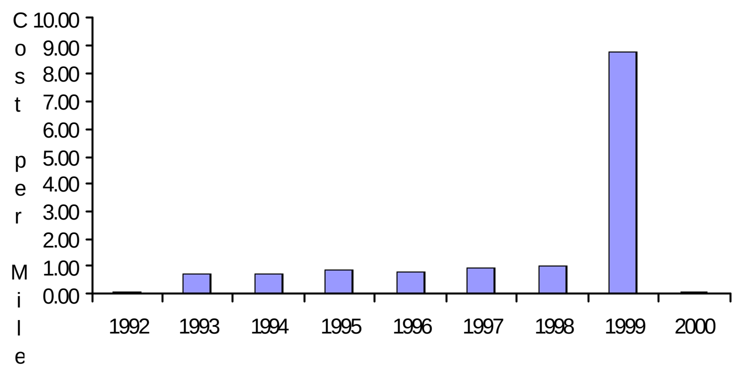


Fig. 2.2.39 Equipment Cost per Mile Pueblo Region

Aurora The Aurora region relies mainly on the sand-salt mix for the roadway traction enhancement as evidenced in its steady application rate of approximately 0.12 tons per lane mile from 1994 to 2000. The region's equipment cost experienced about a 20 cent increase as shown in Figure 2.2.40, when it began to use liquid deicer in 1996. The transitional equipment retooling and also inflation could cause this cost increase.

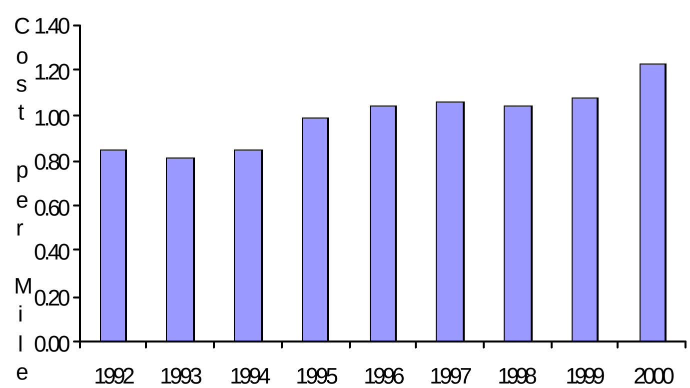


Fig. 2.2.40 Equipment Cost per Mile Aurora Region

Craig Figure 2.2.41 shows that the Craig region has managed to keep its equipment cost steady at an average of about one dollar per lane mile in spite of equipping its sanding trucks with the spreader for liquid deicer in 1999.

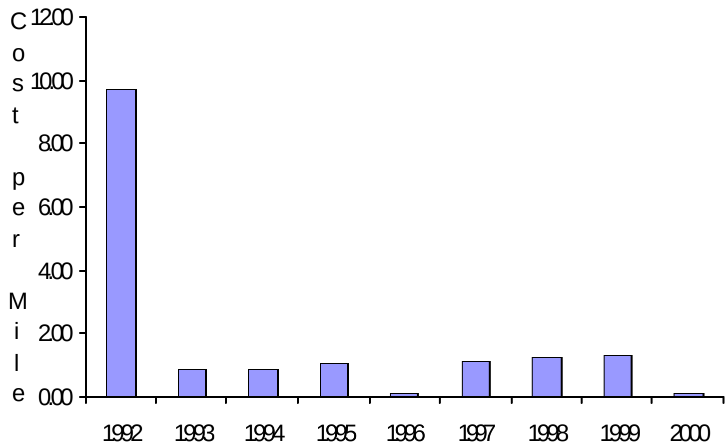


Fig. 2.2.41 Equipment Cost per Mile Craig Region

Alamosa Alamosa was the last region to begin using deicing chemicals. In the fiscal year 2000, it began a limited experiment on the use of deicer. The equipment cost in Figure 2.2.42 is strongly associated with the sanding cost shown in Figure 2.2 19. It may be interesting to compare the impact on both cost and environment between the Alamosa region with little use of deicer and the Grand Junction region with an aggressive deicer program in a future study.

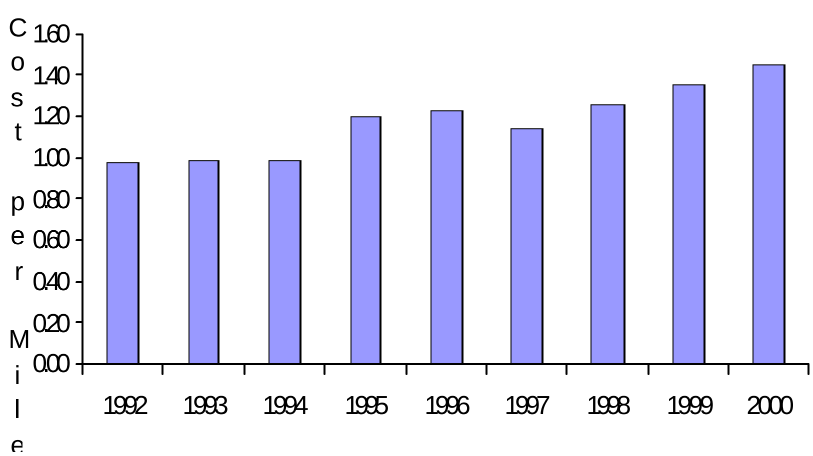


Fig. 2.2.42 Equipment Cost per Mile Alamosa Region

Denver The Denver region followed Grand Junction in adopting liquid deicer in 1994. Note the 20 cents per lane mile increase in equipment cost, which is typical for all other Colorado regions, Figure 2.2.43. This additional cost is more than offset by the benefit that it has received by the substantial reduction in the use of sand. This indicates the use of deicer as a main traction enhancement and ice removal agent in the metropolitan area and the use of sand has become secondary.

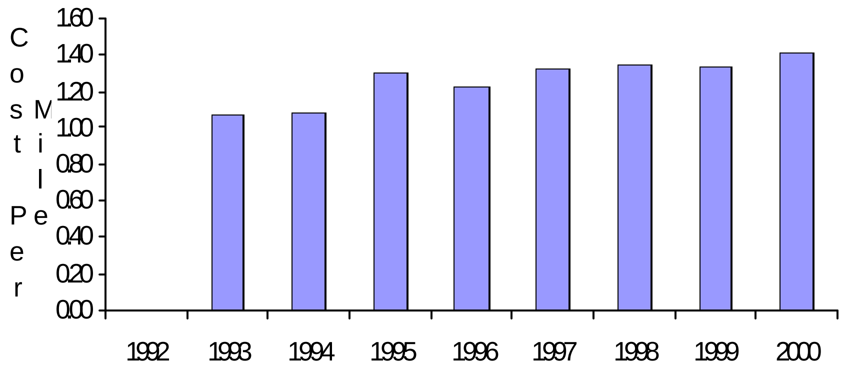


Fig. 2.2.43 Equipment Cost per Mile Denver Region

Eisenhower Tunnel Eisenhower Tunnel region equipment cost is presented in Figure 2.2.44. The material data was incomplete. This makes cost comparisons impractical. In general, its equipment cost per lane mile is much higher than those of other regions in Colorado.

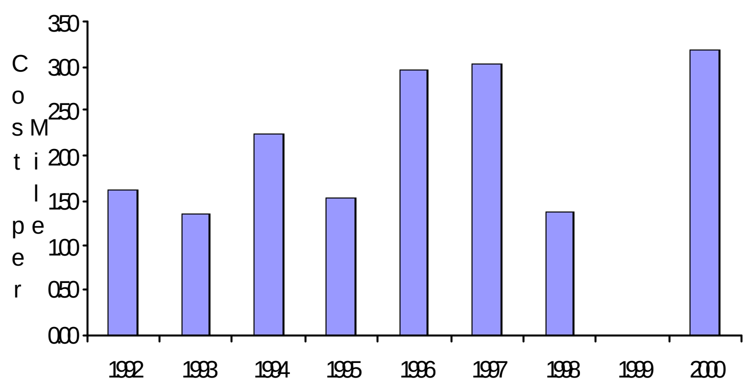


Fig. 2.2.44 Equipment Cost per Mile Eisenhower Tunnel Region

2.3 CDOT Statewide Winter Roadway Maintenance Statistics

2.3.1 Introduction

Because of the drastic differences in regional snow removal, sanding, and deicing practices due to the differences in geology, geography, and snowfall, statewide data is deemed more appropriate for a cost comparison. The statewide annual snowfall for each CDOT fiscal year is used in the study.

2.4 Annual Snowfall

Figure 2.4.1 presents the statewide annual snowfall from 1994 to 2000. Although the compilation is not as complete as desired, it has enough data for making a comparison between the period with little or no deicer use, as in 1994, to the period when the deicer is widespread, as in 2000. If the storm of October 1997, which occurred in fiscal 1998 and delivered 21.9 inches of snow to the Denver area, is removed, the snowfall for the last five years is about 50 to 60 inches. This steady rate gives us a good benchmark to compare cost and materials use statewide.

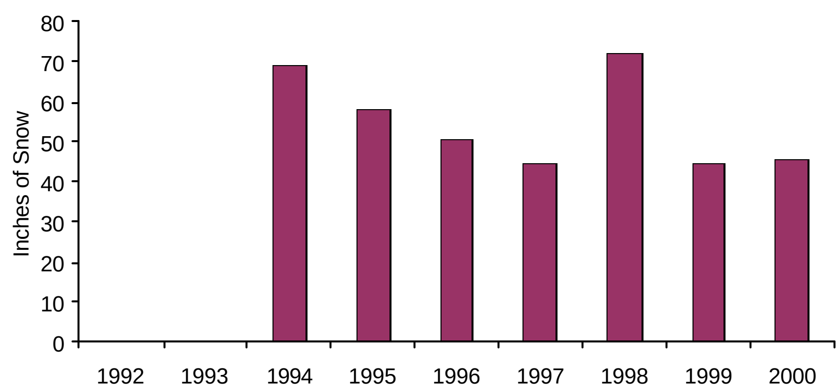


Fig. 2.4.1 Statewide Annual Snowfall

2.5 Maintenance Cost Contributions

2.5.1 Materials Use Statewide

Figures 2.5.1 and 2.5.2 show a definite declining trend in solids use and rising trend for the liquid deicer use. The spike in solids use in 1994 is directly related to the spike in the Pueblo region solid materials use for that year. The representative use of salt in this graph includes the Eisenhower Tunnel region, which used an extensive amount in 1992 through 1994, Figure 2.2.26, for the salt use in the Eisenhower Tunnel region. With these exceptions, the state has been switching over to liquid deicer at an exponential rate since 1994.

When the materials are compared to snowfall we see that more liquid per mile is being applied while annual snowfall remains steady. The abnormally high snowfall in October of 1997, part of fiscal year 1998, does not appear to have affected the amount of deicing and traction improving materials applied to the roadways. This early season storm, which closed major roadways for a short period of time, did not leave our roadways with any large amounts of snow or ice. After just a few days, the temperature warmed up and most of the snow melted quickly. While an exponential growth occurred in the use of liquid chemical deicers, a corresponding exponential decrease of solids use was not observed. This shows that the complete elimination of sand is impractical as some sand is needed in heavy snowfall at some strategically important roadway safety locations, like intersections, steep slopes, etc. This approach of optimal combination of liquid deicers and sand application was also recommended in the 1994 CDOT/FHWA sponsored study on "Environmentally Sensitive Sanding and Deicing Practices."

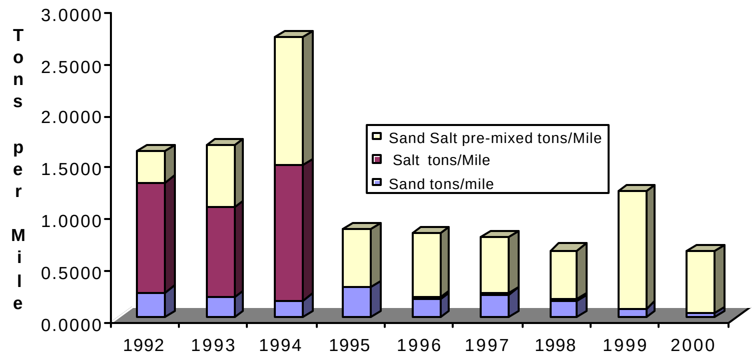


Fig. 2.5.1 Statewide Solid Material Use per Mile

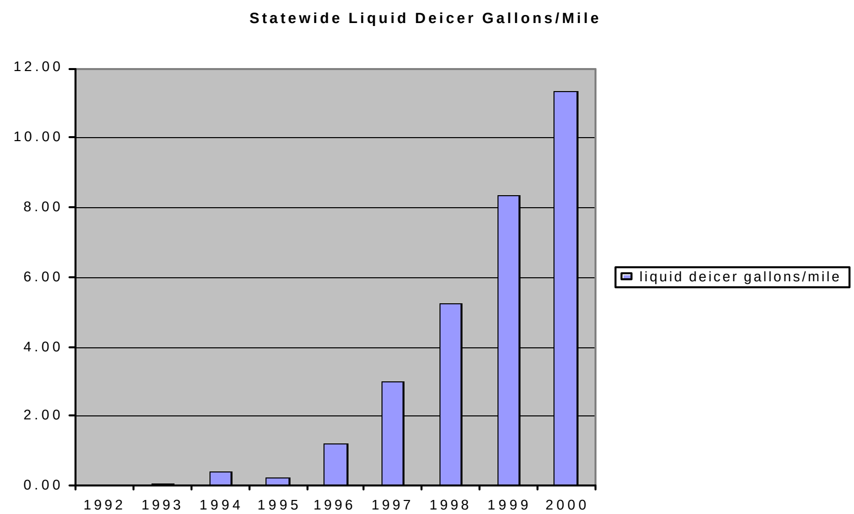


Fig. 2.5.2 Statewide Liquid Deicer Use per Mile

2.5.2 Annual Variation

When materials costs are tabulated statewide on a per mile basis the costs for solid materials are mostly constant. The only driving force behind increased costs of maintaining roads is the addition of the liquid deicer. The added use of liquid deicer has added approximately four dollars per lane mile to maintenance cost associated with snow removal. This represents a 50% increase over 1994 when there were only a few regions using liquid deicer. This increased cost is primarily due to the application of the liquid when snow is forecast. This new trend might seem costly, but when optimally applied in conjunction with the sand use, it could lower the overall cost of the winter roadway maintenance. Figures 2.5.3 and 2.5.4 illustrate the individual costs associated with solid and liquid use.

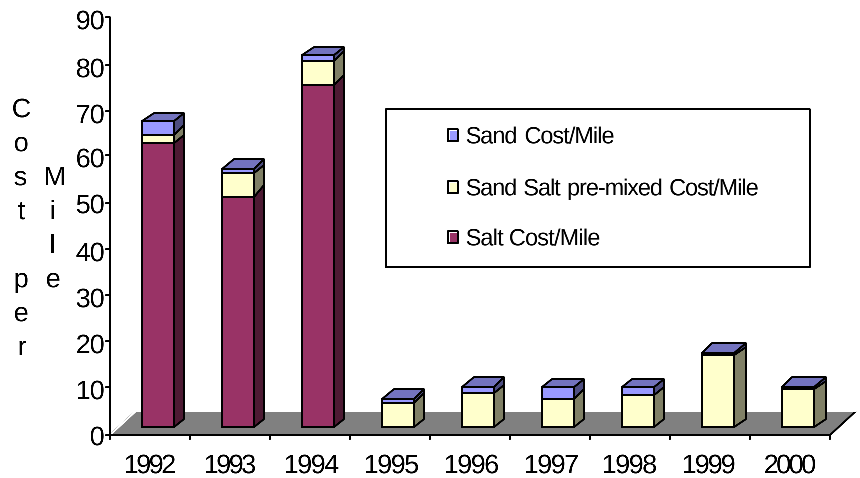


Fig. 2.5.3 Solid Material Cost per Mile

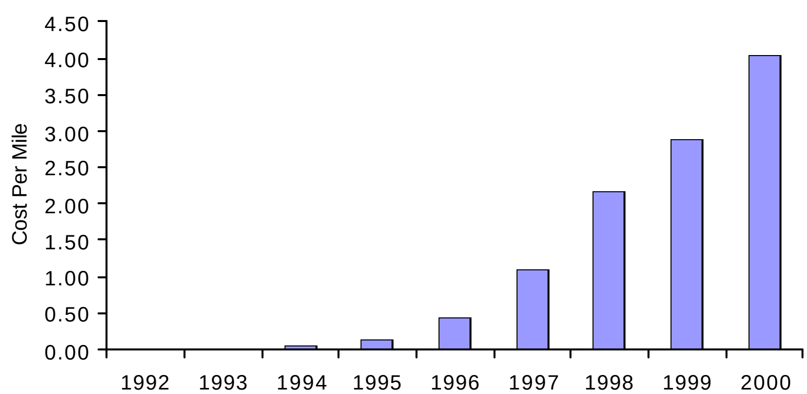


Fig. 2.5.4 Statewide Liquid Deicer Cost per Mile

2.5.3 Statewide Personnel Cost

Figure 2.5.5 shows the personnel cost for maintaining a mile of highway. The increase is most likely due to the introduction and increased use of liquid deicer. This increase is negligible compared to the increase in materials cost per mile.

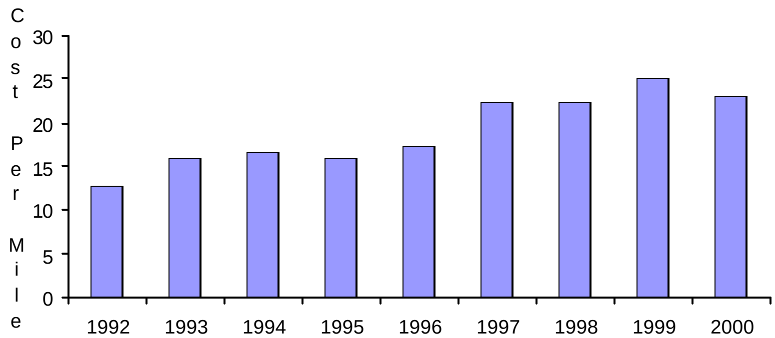


Fig. 2.5.5 Statewide Personnel Cost per Mile

2.5.4 Equipment Cost Statewide

Figure 2.5.6 shows the annual equipment cost per mile for maintaining the Colorado roadways. Equipment cost had remained nearly constant during the five years when liquid use was rising dramatically with the exception of 1999. This might suggest that the same number of maintenance equipment was in service.

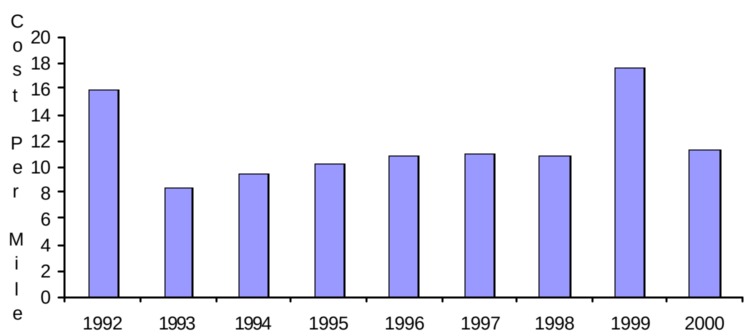


Fig. 2.5.6 Statewide Equipment Cost per Mile

2.5.5 Statewide Total Cost

All statewide costs were combined to produce the statewide total cost for winter roadway maintenance. This total cost was compared to the budget for the same fiscal period in Figure 2.5.7. This data shows that the state usually overspent its budgeted dollars by about 10 to 15% except for 1994, 1999, and 2000. It would be interesting to see the actual cost for fiscal 2001.

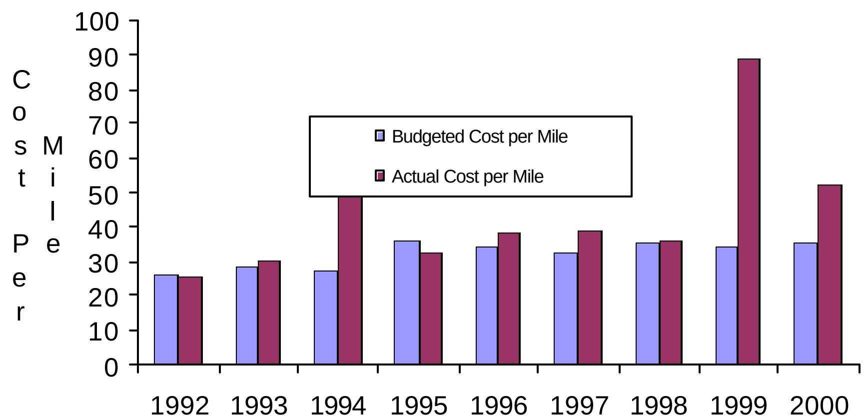


Fig. 2.5.7 Total Cost per Mile

2.6 Annual Use of Sand and Deicing Chemicals in Denver Region

The Denver region has many different types of roadways, two major interstate highways, I-70 and I-25, and many major state highways feeding the major population centers. Besides, it has progressively shifted from strictly sand to increasing use of chemical deicers. Thus, Denver was chosen for further examination of the trend in the policy shift. The material use from other regions will be briefly examined in Section 3.2.

FY1993 In 1993 Denver used primarily a sand-salt mixture as can be seen when we examine Figure 2.6.1. The use of a sand-salt mixture reflects 100% of the $1.51 spent on materials per mile for FY 1993.

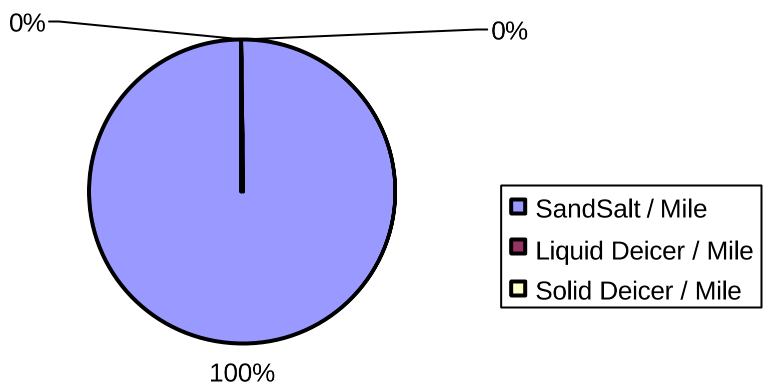


Fig.2.6.1 Denver Region Material Cost Percentage for 1993

FY1994 It is interesting to note that Denver introduced both solid and liquid deicers in 1994 while 77.5% of the material budget was spent on sand-salt mix. The total cost per lane mile was $1.53. The distribution of the material use is shown in Figure 2.6.2.

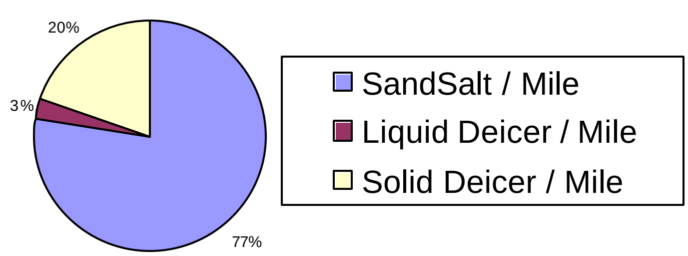


Fig. 2.6.2 Denver Region Material Cost Percentage for 1994

FY1995 Additional dollars were spent on liquid deicers in 1995. Per lane mile cost also increased as more deicer was used. The use of sand-salt mix still expended 73% of the total material budget as shown in Figure 2.6.3. Figure 2.2.23 also shows that the use of sand-salt mix continued to decrease for the study period. The total material cost per lane mile was then $1.95.

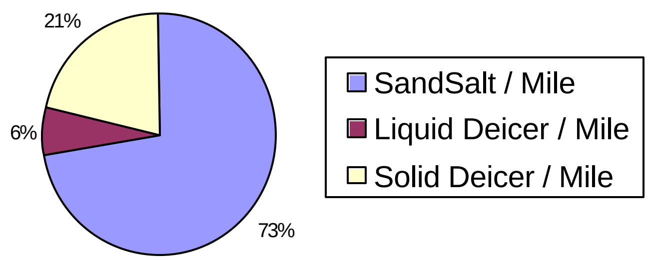


Fig. 2.6.3 Denver Region Material Cost Percentage for 1995

FY1996 Denver shows little change from 1995 to 1996. While liquid deicer use rose, solid deicer use decreased. At $185 per ton the solid deicer was the most expensive. The total cost increase was only less than 2% at $2.00 per lane mile. The trend for decreasing use of solid deicer continued throughout the study period. Figure 2.6.4 shows the percent distribution of the per mile cost for all materials.

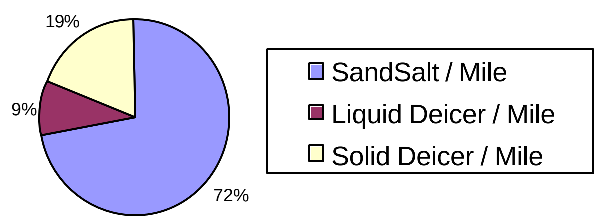


Fig. 2.6.4 Denver Region Material Cost Percentage for 1996

FY1997 Denver significantly increased its use of liquid deicer by 6% in 1997. Meanwhile the solid deicer use dropped significantly and sand-salt use dropped only by 1%. The liquid deicer application rate doubled from 0.35 gallons per mile to 0.70 gallons per mile. Overall cost increased by 10% from $2.00 per mile to $2.20 per mile. This increase can be attributed to the increased use of liquid deicer as shown in Figure 2.6.5.

Fig. 2.6.5 Denver Region Material Cost Percentage for 1997

FY1998 In 1998 Denver traded the use of solid deicer for liquid deicer. The former decreased by 6% from 14% to 8% from 1997 on a percent cost basis. The liquid use doubled again from the year before to a rate of 1.5 gallons per mile, Figure 2.2.24. The total cost, however, remained at the 1997 level because of the simultaneous decrease in the solid deicer use. The 1998 cost breakdown is shown in Figure 2.6.6.

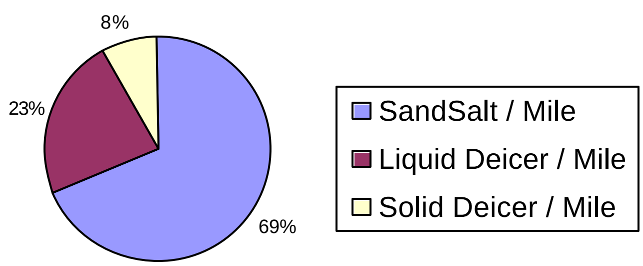


Fig. 2.6.6 Denver Region Material Cost Percentage for 1998

FY 1999 Liquid deicer use increased slightly at the expense of sand-salt mix. It did not continue its increase rate of the previous two consecutive years. The total cost per mile increased significantly from $2.20 to $2.51 per mile. Figure 2.6.7 shows the materials cost distribution for FY1999.

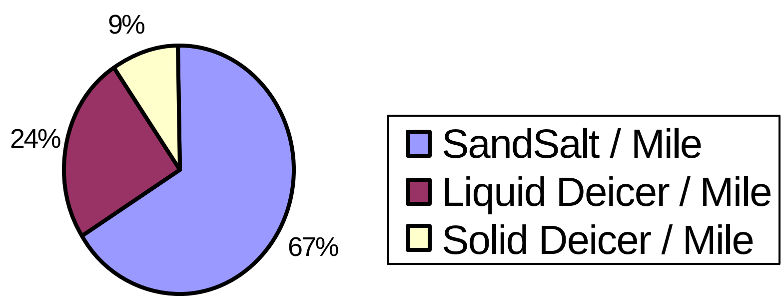


Fig. 2.6.7 Denver Region Material Cost Percentage for 1999

FY2000 This was the big year for the liquid deicer use. It jumped from 24% to 47% of the annual cost. This shift was the result of a 150% rise in the liquid deicer application rate from 2 gallons per mile to 4.5 gallons per mile, Figure 2.2.24. This aggressive use of liquid for FY2000 suggests that it is an effective deicer. As a result of this major shift in liquid use, the overall cost per mile increased by a hefty 25% from $2.51 to $3.13 per mile. Figure 2.6.8 shows the cost distribution for FY2000 at 47% for liquid, 40% for sand-salt mix, and 13% for solid deicer. The use of sand-salt mix dropped from 77% to 40% during the study period. This redistribution of the material cost will be reexamined in Section 10.5, where the windshield damage cost is studied.

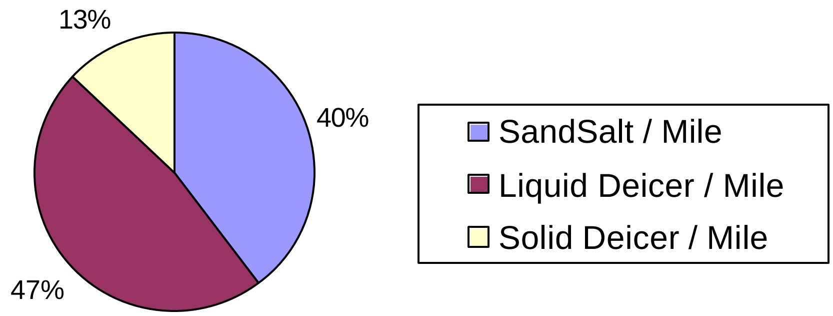


Fig. 2.6.8 Denver Region Material Cost Percentage for 2000

2.7 Conclusions

Winter roadway maintenance practice varies from region to region. So does the cost, because of the variation in geologic conditions and geographic locations, weather patterns, materials availability, environmental requirements, etc. Some areas in the Durango region are so geographically isolated that they have distinctive weather patterns. The same can be said of the eastern plains where snowstorms with blowing and drifting snow are common. The region-specific conditions make a comparison on a regional basis difficult. However, from the material utilization standpoint, the trend is clear. The state as a whole is moving towards the increasing use of liquid deicers, and decreasing use of solid deicer and sand-salt mix at a cost increase of 20 cents per mile per region. This cost increase is attributed to the early application of the liquid when a snowstorm is forecasted. Experiences indicate that the liquid chemicals are more effective in fighting icing conditions when used more as an anti-icing than deicing agent.

Another key factor contributing to the cost variation is the difference in roadway types. Two major interstate highways serve Colorado, I-70 and I-25. This leaves most of the state served by two to four lane highways where sanding practices are very different than clearing a four to six lane interstate. Even though the cost is normalized to the lane mile, the difference in road types still makes cost comparison among regions difficult. Therefore, for the purpose of studying the trend of maintenance practice, the regional statistics were combined to form a statewide database. This makes the correlation study between the maintenance cost and the statewide snowfall possible.

The statewide statistics indicate that 1) The annual total snowfall is 50 to 60 inches except in October of 1997 when 21.9 inches of snow was deposited in Denver in a short time. 2) The statistics for the solid material use and cost show that the solid use has not changed much. This means much of the state has not completed its conversion to liquid deicer as yet. The liquid use, however, has increased about 6 folds since 1994 and is now used throughout the state. Personnel and equipment cost remained steady with some minor fluctuation due to the introduction of liquid deicers and some severe weather.

The Denver region has definitely shifted from the heavy use of solid deicer and sand-salt mix to liquid deicer use. The liquid use has increased many-fold, while the solid deicer and sand-salt mix use has decreased drastically during the study period. This has tremendously improved the air quality in Denver. Besides, the liquid use has avoided the sand sweeping effort, which, in turn, saved the labor and equipment cost. The application of the liquid as an anti-icer has eased the effort of snow plowing and ice removal.

It should be both interesting and necessary to study the effect of the application of liquid deicer on the quality of air and stream and ground water and also the integrity of roadway pavements.

3. **Region-Specific Practices**

3.1 Introduction

Winter roadway maintenance varies from region to region because of the difference in topographical and geographical conditions, weather patterns, population intensity, environmental requirements, traffic volume, materials availability, the needs of the general public in the area, etc. Based on the above factors, each region decides its most effective means of winter roadway maintenance practice. Some may choose to use more sand-salt mix, and some liquid deicer. The choice made will obviously affect the maintenance budget and expenditures.

3.2 Winter Roadway Maintenance Practices for Different Regions in FY2000

The area covered by each region in terms of lane miles is also region-specific. For instance, in the year 2000, Aurora plowed 1,115,000 lane miles of its roadways. Denver is the smallest with only approximately 350,000 lane miles plowed, as shown in Figure 3.2.1. Because of the influencing factors identified in the previous section, winter roadway practice differs significantly. The difference will be presented in terms of the percentage of cost of material as opposed to the quantity of materials used. The average annual cost per lane mile will also be included for reference. The statistics for FY2000 were selected because it was the only year that all materials were tried by all regions.

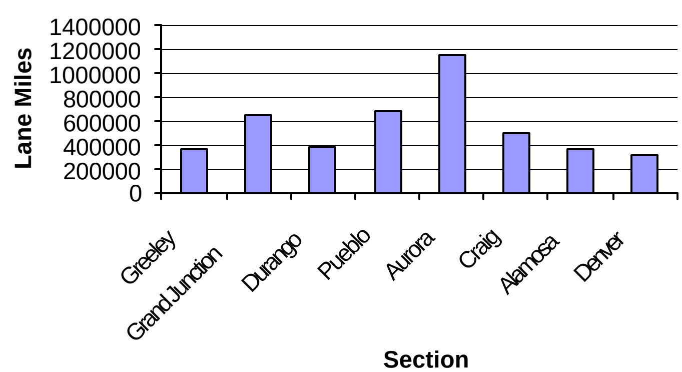


Figure 3.2.1 Lane Miles Plowed in FY2000

3.2.1 Greeley Region

The Greeley region with a plow mileage of 375,000 had a per mile cost of 98 cents for materials in 2000; this cost came largely from using a mix of sand and salt as shown in Figure 3.2.2. This low cost is a result of limited sanding practices, as in only sanding the intersection of many of the state roads in Greeley. While this practice works in less populated areas, it may not be a feasible option for areas like Denver and Aurora.

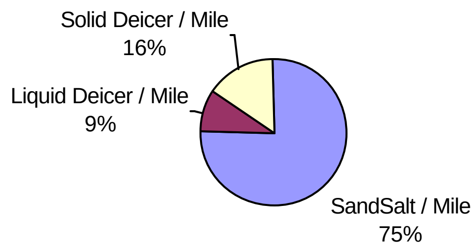


Figure 3.2.2 Material Cost Percentage for Greeley Region FY2000

3.2.2 Grand Junction Region

The Grand Junction region was the one of the pioneer regions for initiating the use of liquid deicer to aid in the snow and ice removal effort. It uses significant amounts of liquid deicer and naturally the liquid cost also constitutes a large part of its material expenditure. Fifty three percent of its FY2000 material cost per lane mile, $2.38 was expended on the liquid, as shown in Figure 3.2.3. It plowed 650,055 lane miles of its roadways. It would be interesting, when funding is available, to isolate Grand Junction for studying the effect of liquid deicer use and the reduction of sand-salt mix use on the insurance cost to the traveling public in terms of the windshield damage cost claimed.

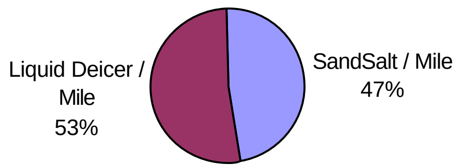


Figure 3.2.3 Material Cost Percentage Grand Junction FY2000

3.2.3 Durango Region

The Durango region was one of the last to use liquid deicer, as the region did not switch until 1998 and even then it use was limited to between 0.6 and 1.4 gallons per mile for the study period. This can be seen in Figure 2.2.9. Figure 3.2.4 shows the breakdown of cost per mile, with solid deicer being the largest contributor to the annual cost at 48% of the total. It is interesting to note that the Durango region still uses some sand; this practice has all but disappeared in other regions. The annual cost per mile spent in the Durango region was $2.45, which is on par with other regions for the year.

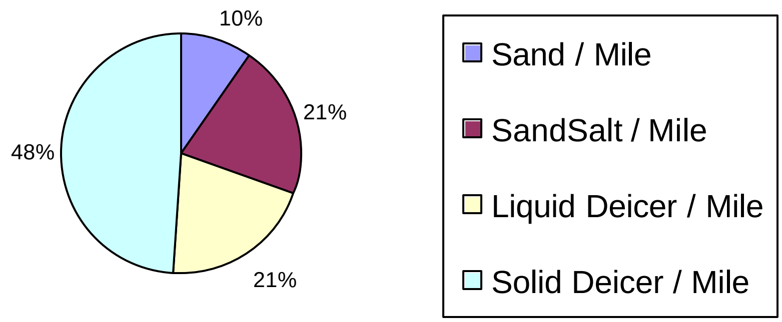


Figure 3.2.4 Material Cost Percentage for Durango Region FY2000

3.2.4 Pueblo Region

Figure 3.2.5 shows the heavy reliance of Pueblo on sand-salt mix with 84% of the total material cost of $1.60 per lane mile on sand-salt mix. Its sanding practices, similar to those in Greeley, might be responsible for the low cost. It applied sand only at some strategic locations, like intersections. Pueblo plowed 700,000 lane miles in FY2000.

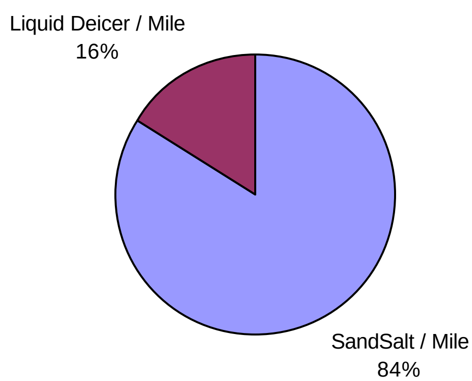


Figure 3.2.5 Material Cost Percentage for Pueblo Region FY2000

3.2.5 Aurora Region

Aurora is the region with the largest number of plowed lane miles at 1,115,000 miles. As shown in Figure 3.2.6, seventy three percent of its annual material expenditure of $1.87 per lane mile was spent on sand-salt mix. The neighboring Denver spent $3.13 per lane mile on material in the same FY2000. This reflects the difference in the winter roadway maintenance practice between the two regions with Denver emphasizing liquid and Aurora sand-salt mix. This indicates that the sand-salt mix is less expensive than the liquid. However, after snow had melted, the Aurora sand sweeping added $0.43 to the maintenance cost compared to the $0.35 added for Denver.

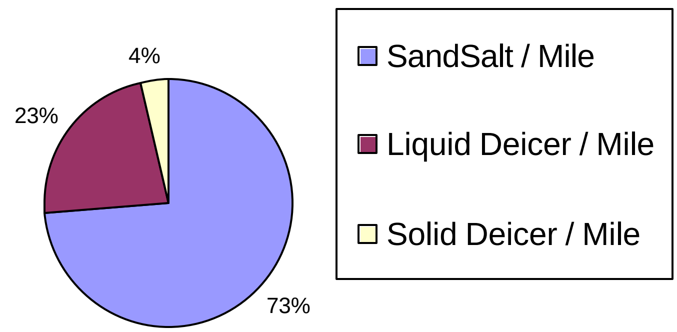


Figure 3.2.6 Material Cost Percentage for Aurora Region FY2000

3.2.6 Craig Region

Figure 3.2.7 shows that the Craig still almost solely relies on sand and sand-salt mix, 99%, for enhancing its winter roadway traction at the cost of $1.65 per lane mile. It plowed nearly 500,000 lane miles. This is attributed to its remoteness, as few major highways traverse the region.

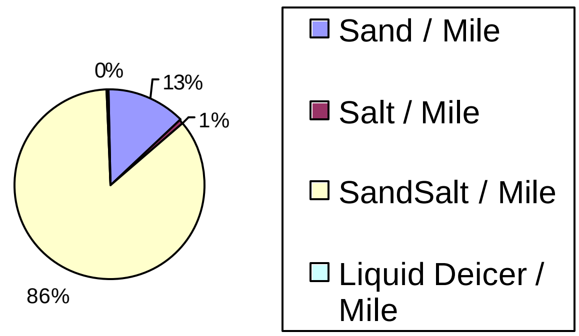


Figure 3.2.7 Material Cost Percentage for Craig Region FY2000

3.2.7 Alamosa Region

As shown in Figure 3.2.8, Alamosa is similar to Craig in its heavy reliance on sand-salt mix as a traction enhancement agent at a material cost of $0.57 per lane mile. It plowed 359,000 lane miles in FY2000. This low cost reflects the sparse nature of its application of sand.

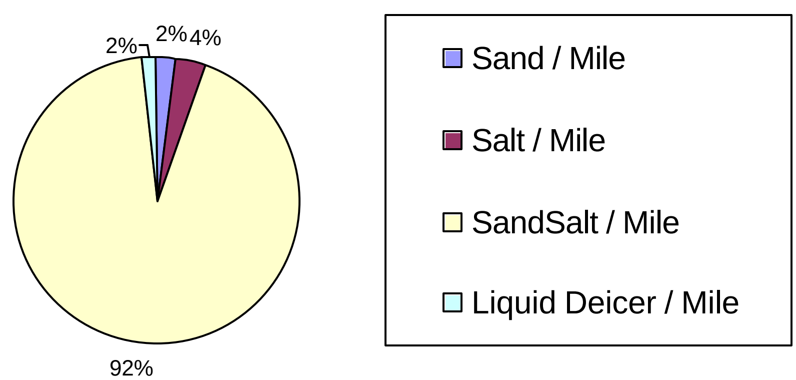


Fig. 3.2.8 Material Cost Percentage for Alamosa Region

3.2.8 Conclusions

As previously mentioned, the materials cost varies greatly among regions because of their differences in geographic location, topographic conditions, population, roadway types traversing the region, and weather patterns. Liquid deicers are more appropriate for heavy population centers with critical air quality concerns and major thoroughfares, like Denver, Grand Junction, etc. The remote regions of the state still rely heavily on sand and sand-salt mix for traction enhancement.

3.3 Characteristics of Sand from Different Regions

3.3.1 Introduction

The size, shape, rock types and grain size distribution of sand are different from region to region. These basic characteristics have significant influence on windshield damage characteristics and are worthy of close examination. The American Society for Testing and Materials (ASTM) specifies a series of sieves each with a specific opening as shown on Table 3.1 for analyzing the grain size distribution characteristics of soils.

Several systems have been developed to classify particle sizes based on their size. The ASTM Particle Size Classification System (Table 3.1) defines and classifies particles according to their ability to pass through certain sieve sizes. A sieve is a manufactured mesh of wire with a specific opening size, as shown in Figure 3.3.2. Figures 3.3.3 and 3.3.4 are samples of the sanding material used in Colorado.

Table 3.1 ASTM Particle Size Classification System

ASTM Particle Size Classification

Sieve Size		Particle Diameter			
Passes	Retained on	(in)	(mm)	Soil Classification	
	12 in.	> 12	> 350		Rock
12 in.	3 in.	3 to 12	75.0 to 350	Boulder	Fragments
3 in.	3/4 in.	0.75 to 3	19.0 to 75.0	Cobble	
3/4 in.	#4	0.19 to 0.75	4.75 to 19.0	Coarse gravel	
#4	#10	0.079 to 0.19	2.00 to 4.75	Fine gravel	Soil
#10	#40	0.016 to 0.079	0.425 to 2.00	Coarse sand	
#40	#200	0.0029 to 0.016	0.075 to 0.425	Medium sand	
#200		< 0.0029		Fine sand	

Figure 3.3.1 Standard Sieve

Figure 3.3.2 Representative Sample of Sanding Material

Figure 3.3.3 Portion of Sample

Figure 3.3.4 Portion of Sample

As shown in Figure 3.3.1, a set of sieves is stacked up in a sequence with the sieve of largest opening on top and smallest opening at the bottom, which is followed by a catch pan for catching the particles finer than the opening of the bottom sieve. A dry sample of soil is poured inside the top sieve and the stack with soil sample is then placed in a sieve shaker and is shaken for about 15 minutes. During the vibration, the sample is screened based on the sieve opening and particle size. Particles finer than a specific sieve opening pass through the sieve and the particles larger than the sieve opening will be retained in the sieve. The weight of soil retained on each sieve is weighed and the data is then used in plotting the gradation characteristic curve.

3.3.2 Preparation of the Sieve Analysis of Sanding Material

The primary purpose for performing the sieve analysis is to delineate the difference in the grain size distribution characteristics of soils used as sanding materials provided by different regions. Before a sieve analysis was performed, a dry material was soaked for at least 24 hours and then washed to remove the dissolvable materials, mainly rock salt, in the mix. This allows the determination of salt percentage in the mix.

3.3.3 Sieve Analysis Procedure

Each region uses its own local sand for sanding its roadways. Thirty-six bags of sanding materials from various storage depots throughout the state were made available for the study. Rock salt was removed from each bag of sanding materials and dried before the performance of sieve analysis. The oven-dried salt-free sand was analyzed for its gradation characteristics. The following stack of sieves were used in the analysis:

Sieve	Diameter (US)	Diameter (Metric)
3/8"	0.3750 inch	(9.500mm)
#4	0.1870 inch	(4.750mm)
#8	0.0331 inch	(2.360mm)
#20	0.0935 inch	(0.8500mm)
#50	0.0117 inch	(0.300mm)
#200	0.0029 inch	(0.074mm)

Each sample was subjected to shaking in a sieve shaker for ten minutes or longer. The sieves were then separated and the soil retained in each sieve was weighed and the data recorded as in Figure 3.3.5 for the preparation of the gradation curve as shown in Figure 3.3.6. The grain size distribution curve presents a relationship between the grain diameter and the percentage of soil passing through each representative sieve. It allows the calculation of some grain distribution characteristic sizes, D_{10}, effective diameter with ten percent of soil passing this specific diameter of sieve opening, D_{30}, D_{50}, and D_{60}. These characteristic diameters are then used to calculate the coefficient of uniformity, C_u and coefficient of curvature, C_c as follows:

Coefficient of Uniformity = $$C_u = \frac{D_{60}}{D_{10}}$$

Coefficient of Curvature = $$C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$$

A poorly (or uniformly) graded soil has a low C_u value with a great portion of soil with similar particle size, while a well-graded soil has a high C_u value with particles of a wide range of particle sizes. Most C_u values of sanding materials in Colorado are less than 20. Soils with smooth gradation curves have C_c values between one and three. Curves with many inflection points represent a gap-graded soil (lacking soil of certain grain sizes). Most of Colorado sanding materials are well-graded sands. Figures 3.3.6, 3.3.7 and 3.3.8 are typical gradation curves.

GRAIN SIZE ANALYSIS

Project	*SANDING PROJECT*	Job No.	
Location of Project	*UCD -Geotech Lab*	Sample No.	*#14*
Description of Soil	*Gravel*	Depth of Sample	*na*
Tested By	*TGG / EG*	Date of Testing	*10/30/00*

Soil Sample Size (ASTM D1140-54)

Nominal diameter of largest particle	Approximate minimum mass of sample, g
No. 10 Sieve	200
No. 4 Sieve	500
3/4 inch	1500

Rock and Salt Mix (grams)	
Mass of dry sample + dish	1020.0
Mass of dish	551.6
Mass of dry sample	468.4

Washed Rock Mix (grams)	
Mass of dry sample + dish	989.2
Mass of dish	551.6
Mass of dry sample	437.6

% Salt= 6.58

Sieve analysis and grain shape

Sieve No.	Diam. (mm)	Mass of Sieve	Sieve + Retained	Mass Retained	% Retained	% Passing
3/8"	9.500	836	836	0	0.00	100.00
4	4.750	736.7	907.7	171	39.08	60.92
8	2.360	453.6	577.6	124	28.34	32.59
20	0.850	634.4	738.6	104.2	23.81	8.78
50	0.300	559.8	591.2	31.4	7.18	1.60
200	0.074	418	421.95	3.95	0.90	0.70
Pan		597.6	600.6	3	0.69	0.01
				437.55	99.99	

% passing = 100 - Σ% retained

Figure 3.3.5 Sieve Analysis Data Sheet

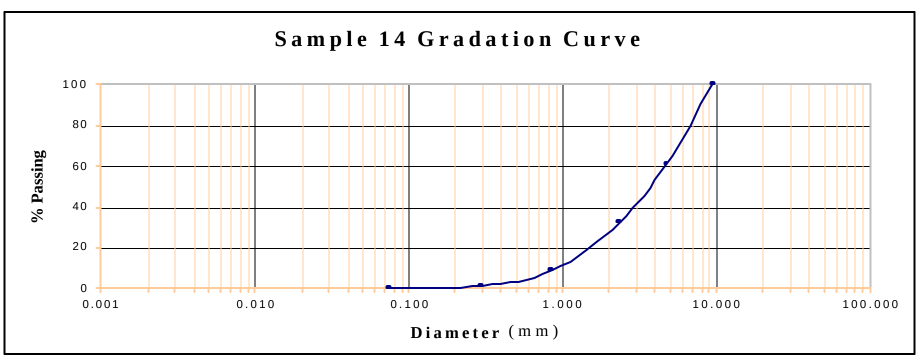


Figure 3.3.6 Distribution Curve

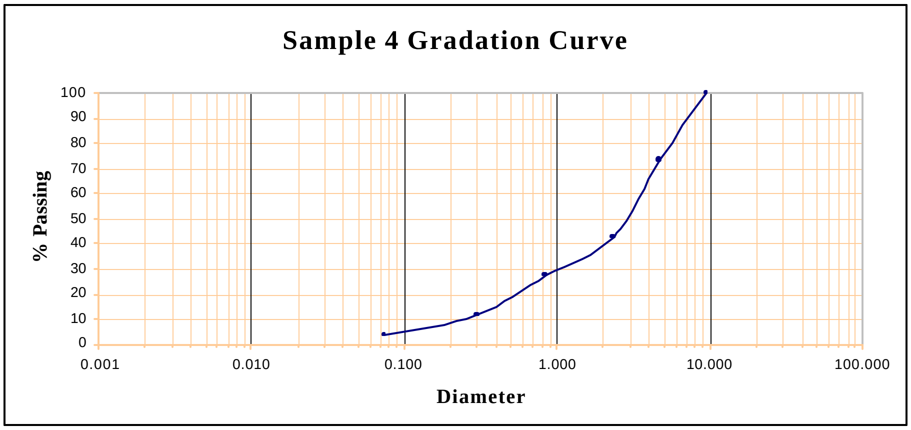


Figure 3.3.7 Distribution Curve Representing a Gap-Graded Soil

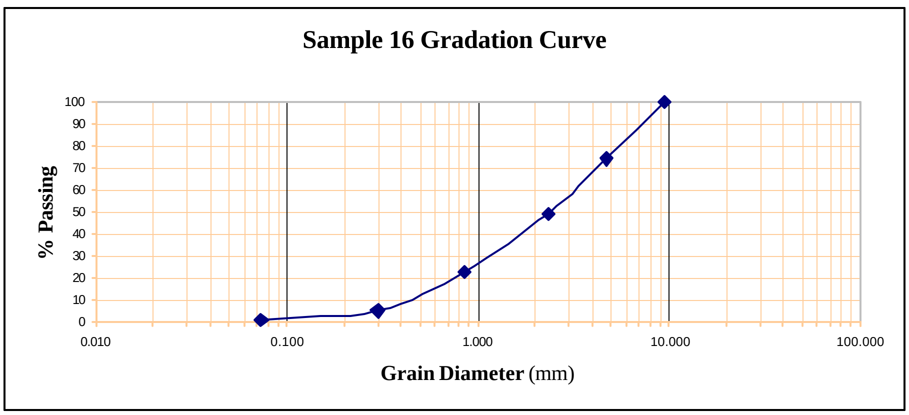


Figure 3.3.8 Distribution Curve Representing a Well-Graded Soil

Figures 3.3.5 and 3.3.6 show that Sample #14 has the following grain size distribution characteristics:

Sieve No	
#200	Approx. 0.7% of the sample is less then 0.0029" diameter
#50	Approx. 1.6% of the sample is less then 0.0117" diameter
#20	Approx. 8.8% of the sample is less then 0.0935" diameter
#8	Approx. 32% of the sample is less then 0.0331" diameter
#4	Approx. 60.9% of the sample is less then 0.187" diameter
3/8	Approx. 100% of the sample is less then 0.375" diameter

The data also shows that Sample #14 contains 6.6% salt. It also has the following critical characteristic sizes and parameters:

D_{10} = 0.875 mm; D_{30} = 2.25 mm; D_{50} = 3.85 mm; D_{60} = 4.9 mm;

$$C_u = \frac{D_{60}}{D_{10}} = 4.9 \big/ 0.875 = 5.6 \text{ ; and } C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}} = \frac{(2.25)^2}{0.875 \times 4.9} = 1.18$$

The result shows that the majority of Sample #14 is a well-graded soil with C_u = 5.6 and C_c = 1.18 and majority grain size smaller than 3/8 inches and greater than 0.0935 inches. Finer grains are actually not a desirable sanding material. Visual inspection shows the material to be sub-rounded. Each sample was subject to the same sieve analysis and results are shown in Table 3.2.

3.3.4 Summary and Conclusions

Among 34 samples tested, six have the uniformity coefficient greater than 10 and fines content greater than 1%, which are quite suitable as sanding materials. Most sanding materials submitted for testing are excellent sanding materials. Quality control of the sanding materials is quite important because of the potential effect on traction enhancement efficiency and air quality in terms of PM-10.

Table 3.2 Sieve Analysis Results for Colorado Sanding Materials

Sieve Analysis Results - Samples 1 through 34									
		Passing Grainsizes (mm)							
SAMPLE	C_U	C_C	D_{10}	D_{30}	D_{50}	D_{60}	Passing #200 (%)	% Salt	
1	2.20	1.12	1.5	2.35	3.08	3.3	0.2	3.41	
2	7.09	0.92	0.392	1	2.00	2.78	1.5	4.06	
3	2.32	1.17	1.55	2.55	3.18	3.6	0.6	2.22	
4	13.80	1.11	0.255	1	2.92	3.52	3.4	0.60	
5	2.17	1.23	1.52	2.48	2.88	3.3	0.2	12.18	
6	1.87	1.19	1.87	2.79	3.30	3.5	1.3	29.44	
7	4.00	1.85	0.795	2.16	2.93	3.18	1.5	25.33	
8	2.01	0.94	2.55	3.5	4.30	5.12	1.0	0.00	
9	3.76	0.94	0.245	0.46	0.72	0.92	1.1	~~-0.09~~	
10	3.24	0.97	0.895	1.59	2.42	2.9	0.8	13.36	
11	9.86	1.22	0.355	1.23	2.50	3.5	0.7	3.72	
12	2.57	1.18	1.355	2.36	3.10	3.48	0.4	2.20	
13	6.39	1.29	0.435	1.25	2.15	2.78	1.0	4.28	
14	5.60	1.18	0.875	2.25	3.85	4.9	0.7	6.58	
15	2.40	1.05	1.48	2.35	3.00	3.55	0.4	28.98	
16	7.31	1.04	0.435	1.2	2.35	3.18	1.0	3.93	
17	2.81	1.10	1.18	2.08	2.90	3.32	0.2	11.19	
18	3.29	1.04	1.08	2	3.00	3.55	1.2	13.19	
19	2.50	1.08	1.35	2.22	2.98	3.37	0.4	8.15	
20	2.44	1.24	1.45	2.52	3.15	3.54	0.7	24.19	
21	3.74	1.60	0.9	2.2	3.00	3.37	1.5	0.65	
22	2.71	1.16	1.25	2.22	3.98	3.39	0.2	3.36	
23	2.26	1.17	1.45	2.36	3.00	3.28	0.4	11.00	
24	12.18	1.52	0.348	1.5	3.42	4.24	1.1	0.58	
25	10.09	0.87	0.345	1.02	2.53	3.48	1.8	3.42	
26	12.48	0.65	0.258	0.736	2.25	3.22	2.7	0.33	
27	8.29	1.50	0.51	1.8	3.41	4.23	1.0	0.00	
28	12.90	1.82	0.2	0.97	2.00	2.58	2.2	2.62	
29	51.70	1.60	0.1	0.91	3.35	5.17	7.4	3.02	
30	9.65	1.22	0.458	1.57	3.34	4.42	1.4	6.20	
31	3.30	1.48	1.05	2.32	3.00	3.46	0.8	0.73	
32	5.75	1.21	0.146	0.385	0.63	0.84	1.8	0.70	
33	3.31	0.56	0.298	0.405	0.66	0.987	0.5	0.12	
34	6.19	0.88	0.315	0.737	1.45	1.95	2.2	21.51	

4. High-Speed Camera for Recording the Airborne Particle Motion

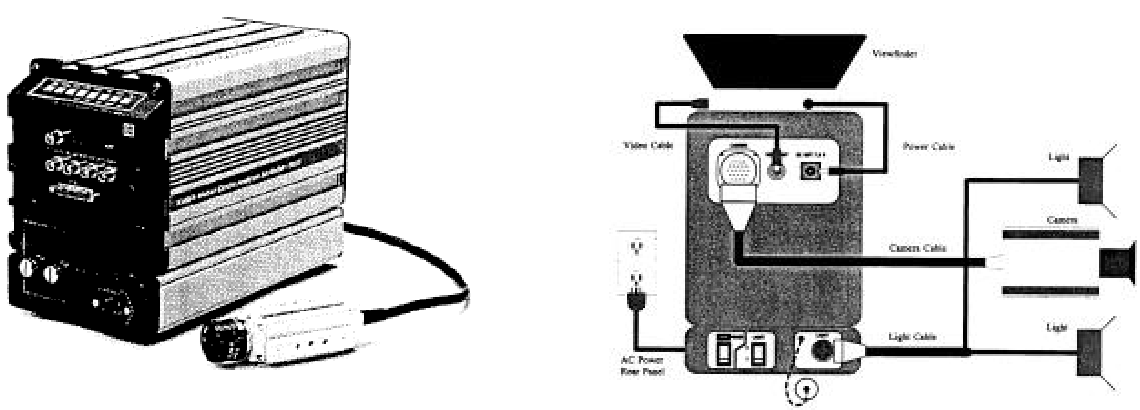
4.1 Introduction

To gain a comprehensive understanding of the dynamics of an airborne particle, high-speed camera photography was performed. Since tire impact takes place in a very short period of time, it was necessary to capture the tire-particle-pavement interaction using a high-speed camera. *The Kodak Motion Corder Analyzer, SR-1000* was used in this study. It has a maximum frame rate of 1000 frames per second and a maximum shutter speed of 1/20,000 second.

4.2 High-Speed Photography

4.2.1 Operation of Kodak High Speed Camera

The Kodak Motion Corder Analyzer, SR-1000 was rented for two weeks. This Motion Corder has the following components: a Processor, Power Supply, Camera and optional LCD Viewfinder or optional Viewfinder with Hi 8 VCR. The Camera, a carrying handle and the viewfinder can be attached to the Processor by sliding their mounting rails into the slots along the top and sides of the Processor case.



(a) (b)

Figure 4.2.1 (a) The Kodak Motion Corder Analyzer SR-1000, (b) and Its Components

Prior to recording, one can change the exposure time, record mode, frame rate, display size, ID number and shutter speed plus several other settings from the control panel on the rear of the Processor. The control panel works in conjunction with the viewfinder to display the needed choices. When in LIVE mode, the ? and ? arrows are used to change the exposure time. The current exposure time is shown in the lower left corner of the viewfinder display. Press the MENU/ENTER button to display the live menu on the viewfinder.

4.2.2 Selecting Start Mode

First, one needs to highlight START MODE and press the MENU/ENTER button. To begin recording, first press the REC READY button and then the TRIGGER button. The processor will record images until every frame in memory has been filled. The processor will automatically stop the recording when the memory is full.

4.2.3 Selecting Frame Rate

Open the Live menu and highlight FRAME RATE. Press the MENU/ENTER button to open the FRAME RATE sub menu. You can select from 500 fps to 20,000 fps depending on the type of the camera. The camera used in this study has frame rate options up to 1000 fps.

4.2.4 Selecting Shutter Speed, an ID Number and Recording

Shutter speed The shutter speed of the camera can be adjusted from 1/1,000 to 1/20,000 depending on the intensity of the available light. When in the Live Mode, use ? and ? arrows to increase or decrease shutter speed. In this study the shutter speed of 1/20,000 was selected most of the time. A higher shutter speed provides clearer pictures.

ID number and Recording Open the Live menu and highlight ID NUMBER. Press the MENU/ENTER button to open the ID NUMBER sub menu. Different ID number is assigned for each filming. If proper composition, focus, and exposure are chosen, press the REC READY button and then the TRIGGER button to start a recording.

4.2.5 Viewing

All playback functions are done in the Display mode. Press the MODE button to toggle between Display and Live mode. Press the ? (Direction) button to playback the recording in memory starting with the frame currently displayed on the viewfinder. Press the ? (Direction) button again to change direction of playback from forward to reverse or from reverse to forward. Use the ? and ? arrows to increase or decrease the play rate. Press the STOP/ESC button once to pause the playback. The word STEP will appear next to the frame number in the data display. One can also view forward/backward frame one at a time using the ? and ? arrows.

Press the STOP/ESC button again to go from step to stop. The word STOP will appear next to the Frame Number in the data display. When pressing STOP/ESC a third time, the viewing skips to the very beginning of the recording by. Pressing STOP/ESC repeatedly will skip the display between the first frame of the recording and the frame where you first pressed STOP/ESC.

4.2.6 Using the Reticle

Open the Playback menu and highlight RETICLE. Press the MENU/ENTER button to open the RETICLE sub menu. Use the ? and ? arrows to move up and down the options. Press the MENU/ENTER button to select the highlighted option. When the reticle is on, the reticle X and Y coordinates appear in the lower right quadrant of the picture and reticle overlays the picture. When return to the display after turning the reticle ON, the X reticle position can be adjusted. Press MENU/ENTER to step to the Y reticle position for adjustment. Press the MENU/ENTER button once more to enter the single step mode.

When in play and the reticle is already on, press STOP/ESC to enter single step mode. Find the frame you want to measure and then press MENU/ENTER button, the word STEP in the data display will change to < X >, then use the ? and ? arrows to change the reticle X coordinate. Press the MENU/ENTER button again and then use the ? and ? arrows to change the reticle Y coordinate. Press the MENU/ENTER button once more to return to the single step mode. Once entered the single step mode, the MENU/ENTER button will cycle through X coordinate adjust, Y coordinate adjust, and single step. You can exit the cycle at any point by pressing the STOP/ESC button or the ? (Direction) button to resume playback.

4.2.7 Velocity Calculations

To calculate the velocity of a particle, the displacement over a time interval must be determined. Since the time interval between two consecutive frames can be determined from the initial recording settings, the particle displacement is calculated using the X and Y coordinate readings of the particle on each frame. Prior to any velocity calculations, coordinate readings must be calibrated by filming an object with known dimensions. The object must be placed at an exact location in the path of the particle, the X or Y coordinate reading of one known dimension of the object is recorded. This reading is then calibrated with the actual dimension. Once this calibration is performed the velocity of any particle can be readily calculated using change in X and Y coordinate readings and time difference between two frames. When the camera location or particle path is changed, a fresh calibration must be made to obtain correct velocity calculations.

5. Slingshot Calibration

5.1 Introduction

To determine the effect of particle impact on windshield damage requires the simulation of particle motion and its flying trajectory. Many factors affect windshield damage: velocity, size, weight, shape, hardness, density and path of a flying particle with respect to the windshield. Slingshots were selected to generate the particle velocity at an appropriate incident angle and height. A supporting wooden frame for the slingshot was designed and manufactured. The assembly is shown in Figure 5.3.1. Particular attentions were paid to the exact extension and the slingshot release mechanism. Ten holes were drilled at the selected exact locations on the wood frame to simulate different extension of the slingshot for producing different particle velocity. To minimize the human effect on the release mechanism, a portable metal tube could be fitted tightly in any hole before a test. A solid metal rod was inserted through a selected hole for a selected extension to simulate a desired particle velocity. Section 5.3 shows an extensive laboratory test program that was carried to calibrate the slingshot for the purpose of producing a calibration curve, the particle velocity versus slingshot extension. The calibrated slingshot was then used in the field tests to establish the extent of windshield damage under impact of different rocks at different velocities.

5.2 Image Capture and Velocity Measurement with high-speed camera

A critical factor in determining the cause and effect of windshield damage is the velocity at which the grain particle impacts a windshield. Thus, the motion of the particle from the ground to the windshield had to be analyzed. Because the particle velocity is too large for naked eye to capture, we chose to analyze the particle motion using a high-speed camera as described in Section 4. A shutter speed of 20,000 frames per second was required to determine the velocity of the particle in flight, Section 4.2.

5.3 Slingshot Calibration (Particle Velocity Versus Extension)

The slingshot, as shown in Figure 5.3.1, was used to achieve sufficient particle velocities simulating the field impact velocity. The elastic chord of the sling was connected to

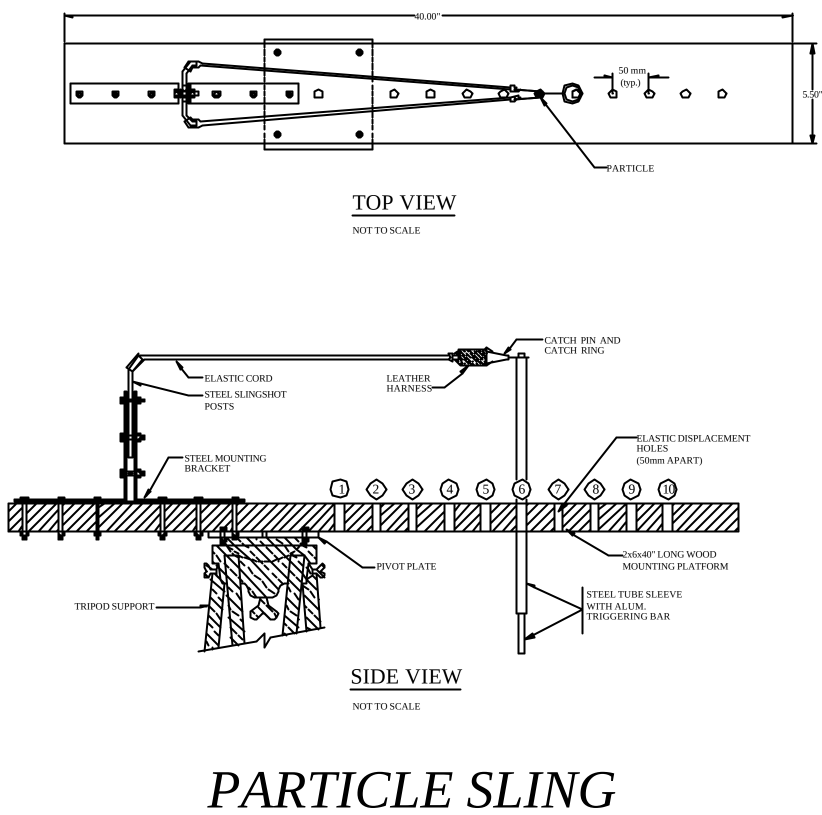


Figure 5.3.1 Slingshot Apparatus Used in Windshield Impact Testing

vertical support posts. The supports were mechanically fastened to a wood platform where it was held stationary. The platform base was attached to a tripod through the wooden platform. A series of holes were bored. The holes were equally spaced in line with the centerline of the sling. The triggering mechanism had two main components: a ½" steel tube and ½" solid metal bar insert. The bar (trigger action) was inserted through the tube and manually operated. The system matched that of a piston mechanism. A receiving ring attached to a leather pouch in turn was attached to the elastic sling. With the elastic sling in its extended position the metal ring was then dropped over the top of solid bar, thus locking the sling in place. Energy now stored in the elastic sling system was ready for release at this point. The magnitude of the strain energy stored in the system was determined by the location of the hole into which the release mechanism was inserted. The elastic deformation correlated directly with the location of the holes centered at 50mm increments. The sling assembly was attached to a tripod with a pivot near the mounting plate. Upon the release of the sling, the strain energy was converted to kinetic energy by which the particle gains velocity and momentum.

Prior to the actual impact test the devise was tested in the laboratory to verify that all desired velocities were attainable. In theory, a moving particle (sanding particle) impacting a windshield is virtually the same as a moving windshield impacting a particle suspended in the air as long as the relative velocity is the same. Therefore, by calibrating the sling, the optimum displacement of the elastic chord (hole location) for field impact tests is determined.

Three different sizes of rocks and a 3/8" BB were used in the calibration tests. The three sizes chosen were small, medium, and large rocks weighing approximately 2 grams, 5.5 grams, and 14 grams, respectfully. The BB weighed 3.48 grams. Each of the test rocks was deployed at different elastic displacements. The displacements correlated with holes number 3, 5, 7, and 9, Fig. 5.3.1. The distance between each of the chosen hole locations was 100 mm. To calculate the velocities, each test was recorded on a high-speed camera. Knowing the time interval between each frame, along with the capability by the camera to measure displacement of an object between two successive frames, the particle velocity of each test was calculated. Refer to Section 8 for velocity calculation procedure.

A total of sixteen tests were performed and recorded. The results showed that velocities ranged from 18 to 84 mph. This proved that the sling system was successful in producing adequate velocities for the actual impact test. Results of the sling tests are shown in Table 5.3.1 and Fig. 5.3.2.

Table 5.3.1 Slingshot Calibration Data
(velocity in km/hr)

Rock Size	HOLE # 3	HOLE #5	HOLE #7	HOLE #9
Small (2.11 grams)	18.336 (29.34)	41.256 (66.00)	61.884 (99.01)	84.804 (135.69)
Medium (5.40 grams)	20.628 (33.00)	34.38 (55.00)	61.884 (99.10)	82.512 (132.02)
Large (14.61 grams)	18.336 (29.34)	34.38 (55.00)	48.132 (77.00)	68.76 (110.02)
BB (3.48 grams)	18.336 (29.34)	48.132 (77.00)	61.884 (99.01)	75.636 (121.02)

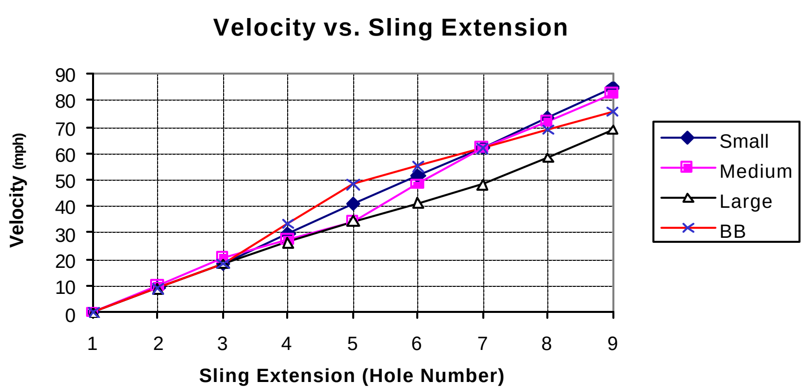


Figure 5.3.2 Slingshot Calibration Curve

5.4 Conclusions

The test has proven the effectiveness of a sling in simulating the velocity of a sanding particle. The particle velocity is proportional to the sling extension. A high-speed camera is necessary for capturing the particle trajectory and determining the particle velocity.

6. Particle Airborne Mechanism and Velocity Measurement

6.1 Introduction

The airborne mechanism of sand particles on highways is quite complicated. The influencing factors include the properties of pavement, sand particles and tires and vehicle velocity. To study this complicated phenomenon, the tire-rod interaction was experimented with in the field, then finite element analysis was carried out to examine how the particle became airborne, and finally, road tests were performed with a vehicle cruising or accelerating. A high-speed camera (HSC) successfully captured the sand particle trajectory during the road test. The HSC images were used in the calculating the particle velocity.

6.2 Tire-Rod Interaction

The mechanism that bounces a sand particle off the pavement is influenced by the properties of tire, particle, pavement and vehicle velocity. The simplest case is when a particle resting on the pavement is rolled over by a slowly rolling tire. To simulate this tire-particle interaction, particles were represented by rods of different sizes and stiffness in an attempt to visualize the deformed shape of rod, pavement, and tire. Wooden and metal rods of different diameters were used in the experiment. Only the deformed shape of the tire was observed. The deformation of the pavement and rods is relatively small and cannot be visualized without special instruments.

A still digital camera was used to record the deformed shape of the tire, particle and pavement system. It was found the tire deformed much more severely than the rod and pavement as shown in Figure 6.2.1. When the rod was much stiffer than the tire, the following sequence of events took place: the tire deformed upon contact with the rod, the tire rode on top of the rod with the maximum tire deformation, the tire rolled over the rod and eventually the tire ejected the rod as observed and shown in the sequence in Figure 6.2.1. This test presented a good simulation of the tire-rod-pavement interaction. Under high pressure a tire embraced a small diameter rod as shown in one of the field tests, and the same phenomenon was expected to happen for the small particle of sand or gravel. The deformed shape of the tire was recorded with digital camera presented in Figure 6.2.1 and figures in Appendix E. Three different types of rods were used in the tests, 2-in steel rod, 1-in wooden rod, and ¾ inch aluminum pipe. A Michelin tire from a regular passenger car was used in the test. The test was carried out on the R Parking Lot at the University of Colorado at Denver, Auraria Higher Education Center.

Figure 6.1a

Figure 6.1b

Figure 6.1c

Figure 6.1d

Figure 6.2.1 Tire-Rod Interaction Test

In performing the experiment, a cylindrical rod was first placed on the surface of the pavement, the passenger car was then driven to slowly run and, eventually, roll over the rod. The tire pressure was 32-psi. The deformation of the tire was recorded at different stages of embracement and identified by the fringes on the tire surface. At partial contact the tire deformation was small, it increased with the progression of the test, and it was largest when the tire was directly over the top of the rod. The tire pressure is also expected to affect the deformation characteristics of the tire-rod-pavement system.

To better understand the system deformation characteristics and the particle bouncing mechanism, finite element analyses were performed to simulate the pavement-particle-tire interaction under a cruising vehicle as shown in Section 6.3, where a vertical load was applied to the top of an elastic particle sitting on the elastic pavement surface. The particle was assumed to be much stiffer than the pavement. The result showed the vertical projectile motion of the particle upon the release of the imparted vertical load. In future studies, a more realistic analysis should be attempted by pressing a real tire on particles of different sizes under different tire pressures and vehicle velocities. The release of the strain energy imparted into the system during the load application might have caused the vertical projectile motion of the particle.

6.3 Finite Element Analysis of Airborne Mechanism

6.3.1 Introduction

High-speed camera recordings revealed that, when under a cruising speed, particles are moving upward immediately after the tire passes over them rather than being picked up by the tire treads and thrown into the air. This behavior is best explained by the release of the stored strain energy both in the particle and the pavement during the loading process by a vehicle. Upon unloading this strain energy is transferred into kinetic energy that results in upward motion of the particle.

In order to verify the bouncing of sand particles due to impact loading induced by the tire of the vehicle a simple mesh was created using computer code TrueGrid. FE analyses were performed using 3-D Implicit Finite Element Code NIKE3D. NIKE3D was developed at the Lawrence Livermore National Laboratory (LLNL) and made available to University of Colorado at Denver (UCD) via a special collaborative agreement. An impact load of 450 lbf was applied on top of the particle in 0.004 sec (0.002 sec loading and 0.002 sec unloading). At the end of each analysis recoil velocity of the airborne particle was obtained. Analysis results showed that the particle's recoil velocity is strongly dependant on material property of both particle and pavement.

6.3.2 Finite Element Analysis Computer Code NIKE3D

NIKE3D developed at Lawrence Livermore National Laboratory (LLNL) for defense program applications provides a powerful tool that can be used to analyze the response of any structures to a static/dynamic load. Computer simulation of nonlinear behavior is quite complex and the nonlinear finite element computer programs developed at the LLNL are among the world's most powerful programs for performing nonlinear analysis.

NIKE3D is an implicit three-dimensional finite element code for analyzing the finite strain static and dynamic response of solids, shells and beams. A number of material models are incorporated to simulate a wide range of material behavior including, elasto-plasticity, anisotropy, creep, and rate dependence. Arbitrary contact between independent bodies is handled by a variety of slideline algorithms. These algorithms model gaps and sliding along material interfaces, including frictional interface.

6.3.2.1 Solution Procedure

In NIKE3D, several nonlinear solution strategies are available, including Full-, Modified-, and Quasi-Newton method. By default, NIKE3D uses the BFGS method. An extensive set of diagnostic messages has been incorporated into the quasi-Newton solvers to allow their convergence progress to be monitored.

NIKE3D is based on updated Lagrangian formulation. During each load step, nodal displacement increments, which produce a geometry that satisfies equilibrium at the end of the step, are computed. After obtaining updated displacement increments, the displacement, energy, and residual norms are computed, and equilibrium convergence is tested using user-defined tolerances. Once it converges, displacements and stresses are updated and proceed to the next load step. If convergence is not achieved within the user-specified iteration limits, an automatic time step controller adjusts the time step size and proceeds.

6.3.2.2 Element/Library

NIKE3D utilizes a relatively small set of elements. All elements use low order interpolation, requiring no midside node definitions. This approach chooses highly efficient elements over more costly higher order elements. The available elements are solid, beam, and/or shell elements. Eight node solid elements are integrated with a 2x2x2 point Gauss quadrature rule. Four node shell elements use 2x2 Gauss integration in the plane, and one of many available schemes for integration through the thickness. Two node beam elements use one integration point along the length, with many options for integration of the cross section.

6.3.2.3 Interface Formulation

NIKE3D uses a penalty formulation for the slidelines with debonding/rebonding and frictional sliding capabilities (Hallquist 1978, 1985)[1]. Penetration resistant springs, named penalty "springs" are automatically generated between contact surfaces when the inter-material penetration is detected. These springs produce contact forces that are proportional to interpenetration depth. Figure 4 shows the penetration of node “m” into another material where the contact force F_s is given by:

$$F_s = kd$$

[1] Hallquist, J. 0. (1978). "A Numerical Treatment of Sliding Interfaces and Impact." Computational Techniques for Interface Problems, AMD Vol. 30, K. C. Park, D.K.Gartling (eds), ASME, New York, pp. 117-133.
Hallquist, J. 0., Goudreau, G. L., Benson, D. J. (1985). "Sliding Interfaces with Contact-Impact in Large-Scale Lagrangian Computations," Computer Methods in Applied Mechanics and Engineering, 51, pp. 107-137.

where κ is the spring constant and δ is the amount of penetration. The constant κ is defined as:

$$k = \frac{f_{SI} K_i A_i^2}{V_i}$$

where K_i, A_i, and V_i are bulk modulus, area and volume of the penetrated material, respectively. f_{SI} is called penalty scale factor, which allows the user to control the penalty spring stiffness. By choosing relatively stiff penalty springs, the interpenetration can be reduced to insignificant values. Frictional behavior is modeled with Coulomb friction with the coefficient of friction μ taken as 0.5 for the particle-pavement interface.

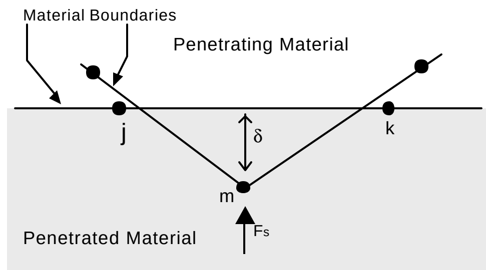


Figure 6.3.1 Penetrating of node "m" into the other material

6.3.3 Finite Element Mesh

Figure 6.3.2 shows the components of the tire-particle-pavement model. Gravitational field and impact load are applied in time domain with time increments of maximum 0.0002 seconds. When divergence is detected time step increment is automatically reduced by NIKE3D.

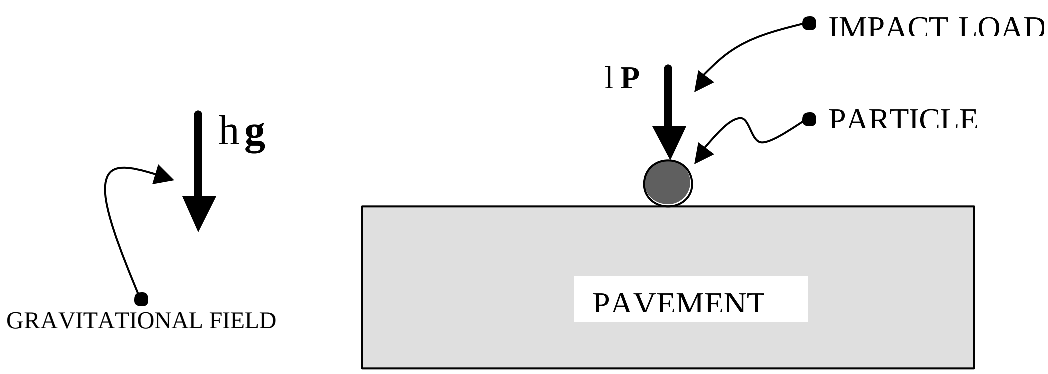
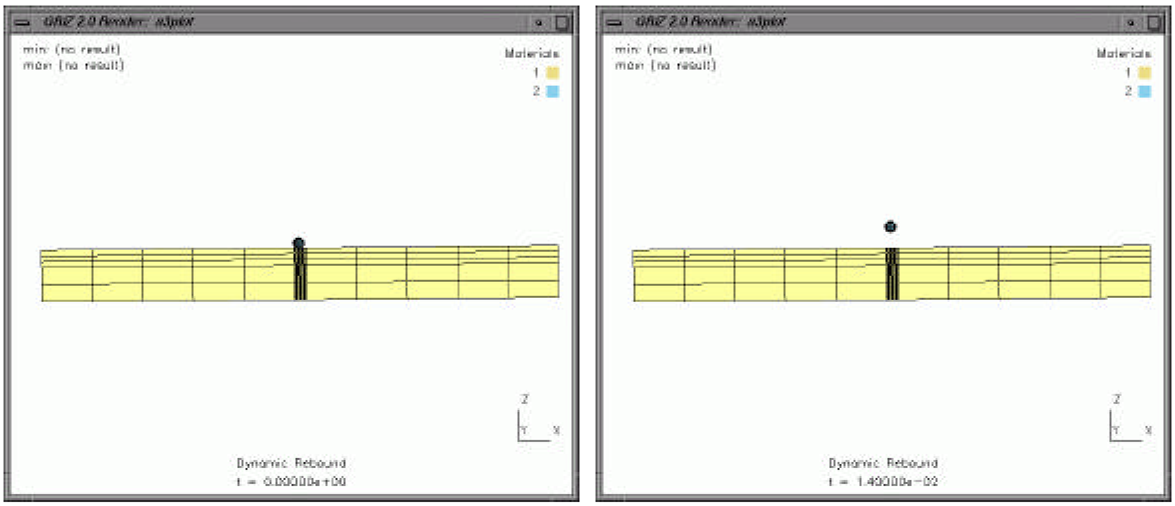


Figure 6.3.2 Illustration of Particle-Pavement-Load Interaction

In the FE model, a portion of the pavement with dimensions of 9x9x1 ft and 0.066 ft diameter soil particle was modeled as solid parts using 8 noded brick elements. The FE mesh was generated using TrueGrid© software. Fixed boundary condition is assumed at the bottom of the pavement (X, Y, and Z motion is constrained). Lateral movements of pavement boundaries are restricted. The particle is assumed to move freely only in Z (vertical) direction. Figures 6.3.3 (a and b) show FE Mesh before and after impact loading respectively.



(a) (b)

Figure 6.3.3 FEM Mesh before(a) and after(b) Impact Load Applied on the Particle

6.3.4 Material Properties

Linear elastic model was used to model both pavement and particle. Material parameters are listed in Table 1 for each case. CASE 1 is for a granite particle and flexible pavement. In CASE 2 the effect of particle stiffness on recoil velocity was investigated by reducing the Young's modulus (E) of the particle by 50%. Finally, in CASE 3, the same FE analysis was performed for granite particle on a concrete pavement to see the effect of pavement stiffness on recoil velocity.

Table 6.3.1 Material Properties Used in the FE analyses

	Linear Elastic Parameters	**PARTICLE**	**PAVEMENT**
CASE 1 Granite Particle & Flexible Pavement	E (10^6 psf)	450	2.16*
	γ (pcf)	145	125
	ν	0.15	0.2
CASE 2 Less Stiffer Particle & Flexible Pavement	E (10^6 psf)	225	2.16
	γ (pcf)	130	125
	ν	0.15	0.2
CASE 3 Granite Particle & Concrete Pavement	E (10^6 psf)	450	3.14♣
	γ (pcf)	145	140
	ν	0.15	0.2

6.3.5 Analysis Procedure

For all FE analyses the following assumptions were made:

- No turbulent effect,
- No air resistance,
- No inter-particle interaction effect,
- No pressure on pavement due to tire-pavement contact,
- Both particle and pavement are assumed as linearly elastic materials,
- Particle can move in vertical direction only,
- Impact load is applied vertically right on top of the particle,

* Typical value for Flexible Highway Pavement, E. J. YODER, “Principles of Pavement Design”, 1959. Particle’s Young’s modulus is reduced by 50%.

♣ Young’s Modulus for concrete.

- Duration of impact is 0.004 sec,
- Maximum impact load is 450 lbf.

FE Analysis has two stages:

Stage 1: Static Analysis (Gravitational Load) During the first 0.002 sec. gravitational load is applied incrementally to the model by pseudo-static analysis in time domain with time intervals of 0.0002 sec. Gravitational load is kept constant during second stage of analysis as shown in Figure 6.3.4.

Stage 2: Dynamic Analysis (Impact Load) After completion of gravitational load, dynamic analysis is started with 0.0002 sec. time intervals. Dynamic Analysis is ended at 0.008 sec. Figure 6.3.5 shows time history of impact load factor λ. When λ is equal to one, the load P reaches a maximum value.

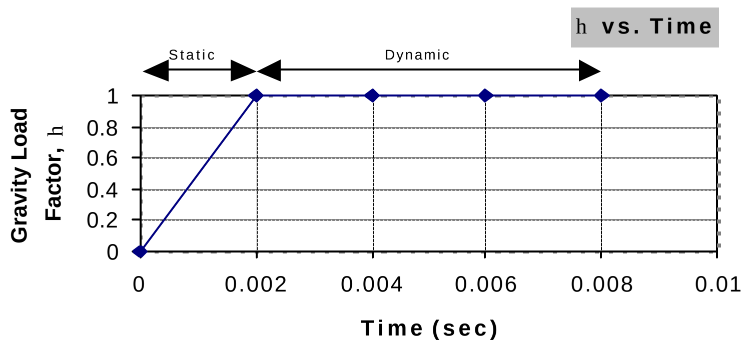


Figure 6.3.4 Gravity Load Factor vs. Time

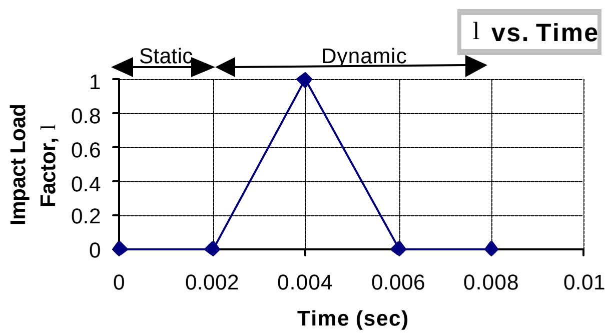


Figure 6.3.5 Impact Load Factor vs. Time

6.3.6 Analysis Results

At the end of each FE run, particle *recoil velocity* and *pavement deformation* time histories were gathered. As shown in Figure 6.3.6, Node 2711 was selected to obtain the recoil velocity. Maximum pavement deformations were obtained from the vertical displacement time history of the Node 1293 as shown in Figure 6.3.7. Results are summarized in Table 6.3.2.

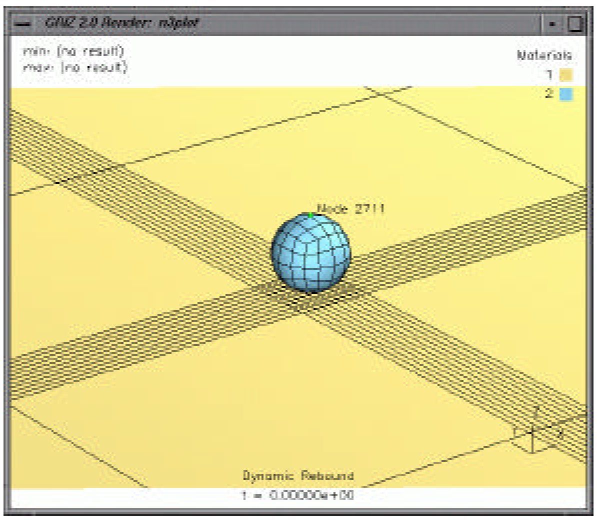


Figure 6.3.6 Location of Node 2711

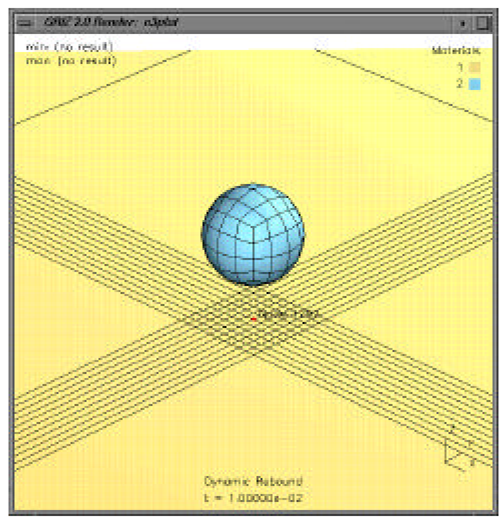


Figure 6.3.7 Location of Node 1293

Table 6.3.2 Recoil Velocity of the Particle and Maximum Vertical Deformation of the Pavement

		CASE 1 Granite Particle & Flexible Pavement	CASE 2 Less Stiffer Particle & Flexible Pavement	CASE 3 Granite Particle & Concrete Pavement
Recoil velocity of Node 2711	m/s	3.7	2.20	2.85
	ft/s	12.14	7.21	9.35
Max. vertical deformation of pavement at Node 1293	m	0.0024	0.00235	0.00176
	ft	0.0079	0.0071	0.00577

6.3.7 Conclusions

As seen from Table 2 CASE 1 (Granite Particle on Flexible Pavement) has a maximum recoil velocity of 12.14 ft/s. In CASE 2 reducing particle stiffness resulted in less recoil velocity of 7.21 ft/s. In CASE 3, using concrete pavement instead of flexible pavement, recoil velocity is 9.35 ft/s, which is smaller than CASE 1. According to the results above, the less stiff particles will lead to low recoil velocity for flexible pavements. Stiffer pavements, such as concrete, also cause less recoil velocity for the same particle stiffness.

It can be concluded that recoil velocity of the particle strongly depends on the particle and pavement material properties. To obtain a better understanding of particle-pavement-impact load interaction a parametric study must be performed. The effect of the following parameters on recoil velocity must be investigated:

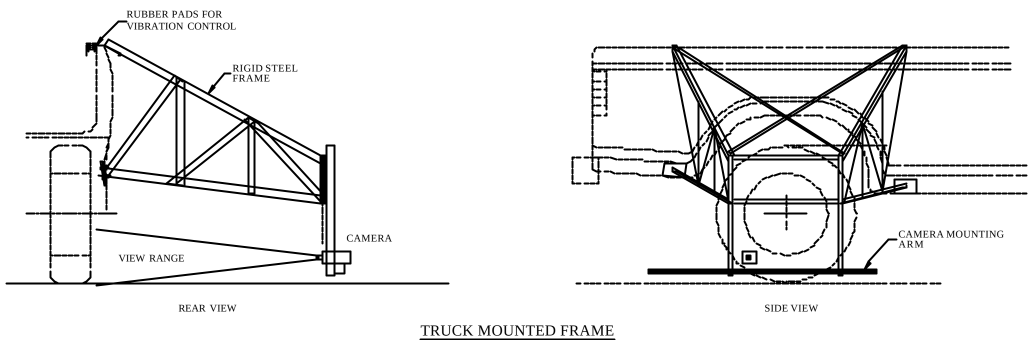
- Density of the particle
- Size of the particle
- Young’s modulus of the particle
- Young’s modulus of the pavement
- Maximum impact load
- Duration of impact.

6.4 Design of Truck-Mounted Camera Frame

Filming the particle trajectory in highway driving is critical to this study. It not only provides the particle trajectory, but its velocity. To capture this action, a camera has to be mounted on a test vehicle at an appropriate location with a maximum vision field. The camera mounting position was chosen at an appropriate distance from the side of the tire only a few inches above the pavement as shown in Figure 6.4.1 to maximize the vision field. For a video camera it was decided that the view should encompass the tire as well as the bumper. This would allow the analysis of the particle path behind the tire. To capture this the video camera had to be mounted at a distance six feet from but perpendicular to the side of the vehicle but close to the pavement.

A computer-drafted design was developed prior to the construction of the camera-mounting frame in Figure. 6.4.1. The frame was constructed of welded angle steel and Uni-strut (C-Channel). The vehicle velocity, as high as 60 mph, is anticipated during the road test. At this velocity the vibration of the mounting frame becomes an important problem. Rubber gaskets were used between the mounting frame and the side fender of the test truck. At the end of the mounting frame, a C-channel was installed for horizontal positioning of the camera. A special mounting plate was developed for attaching and positioning the camera and the high-speed lens.

The frame was also fitted with a halogen lighting system to counter the shadowing effect of the fender wells and the mounting frame. During the video road test, a plywood deflector was installed to prevent the flying particles from the front wheel from entering the camera vision field.



a) Front view b) Side view

Figure 6.4.1 Truck-Mounted Frame for Camera Mounting During Road Test

6.5 Road Tests Recorded with Truck-Mounted Video Camera

Truck-mounted camera tests were initially performed with a regular commercial camcorder with shutter speed of 30 frames per second. The purpose was to test the feasibility of the mounting frame for the eventual adoption of the digital HSC. No velocity measurement was attempted because of the low shutter speed of the camcorder. The initial trial runs using an arbitrary sand mixture placed by CDOT sanding truck indicated the camera mounting extension was feasible for the road test with a HSC.

6.6 Road Tests Recorded with High-Speed Camera (HSC)

6.6.1 Truck-Mounted HSC Tests

In this test series, a HSC was used to capture the particle trajectory during vehicle motion. Two different camera positions were tried: stationary and moving with the test vehicle. Three different types of sand were used: fine, medium, and large grained. The frontage road east of Tower Road was used as the test site. Each material was placed in a 50-ft long section, as shown in Figure 6.6.1. The test was recorded for the entire test length of 150 feet at a shutter speed of 1/20,000 of a second. The road tests were performed at different accelerations including zero, i.e., at a constant cruising velocity. Ten tests were performed as shown on Table 6.6.1.

During trial runs, the flying particles from the front wheel were observed to enter the vision field of the rear wheel. A plywood board was installed on the front face of the mounting frame to alleviate the problem. This allowed an improved view of the particle motion. The camera was slightly tilted to enhance the visibility of the entire tire in action and to include the tire-pavement contact area in the camera vision field. Figure 6.6.3 shows a recorded frame during the road test. The blurry view and low contrast background made it difficult to trace the airborne particle. Thus, no particle velocity measurement was attempted.

6.6.2 Stationary HSC Tests

To obtain a clearer picture we decided to keep the camera stationary at the ground level and drive the truck with varying speeds. The location of camera is shown in Figure 6.6.1. By recording the front tire alone it was expected to avoid all the disturbances mentioned above. To increase the picture quality a dark color panel was placed in the background. Clear recordings were obtained. Figure 6.6.3 shows a recorded frame when particles are in flight. Particles could be seen clearly and it was possible to trace particles and perform velocity calculations. After analyzing the recordings it was observed that particles started to move upward immediately after the tire rolled over them. In other words, particles were not picked up and thrown into the air by the tire treads as frequently believed. We concluded that particle motion was initiated by the rebound of pavement. This conclusion is also confirmed by finite element analyses in Section 6.3. More detailed tests are needed to confirm the mechanism of the particle airborne. Including calibration, nine tests were performed as shown on Table 6.6.1.

A Kodak high-speed camera monitored all road tests. Tests were performed either at different cruising speeds or while the test vehicle was accelerating. The digital images indicated that, at a cruising velocity, sand particles traveled initially in the vertical direction and then followed the vehicle and traveled forward. This forward motion was most likely attributed to the aerodynamic forces generated by the moving vehicle. Figures 6.6.2 and 6.6.3 show two frames of digital pictures, in which particle position coordinates were shown at two different instances of time. Thus, the particle travel distance and elapsed time can be calculated, and further the particle travel velocity can also be calculated. This proved that the high-speed digital camera was effective in capturing the particle flight trajectory.

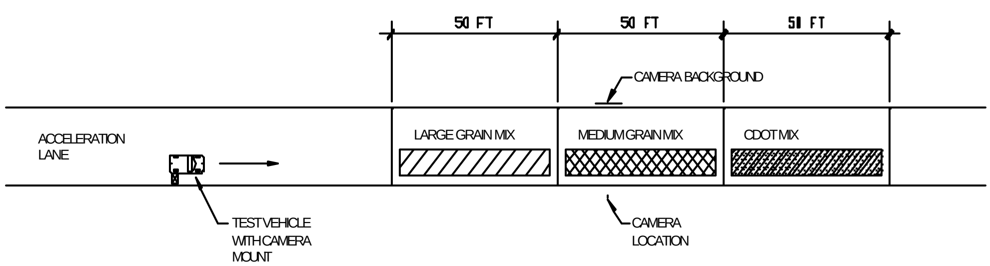


Figure 6.6.1 Test Track on Frontage Road Parallel to I-70 and East of I-225 in Region I

Figure 6.6.2 A Screen Shot from Truck-Mounted Camera Test

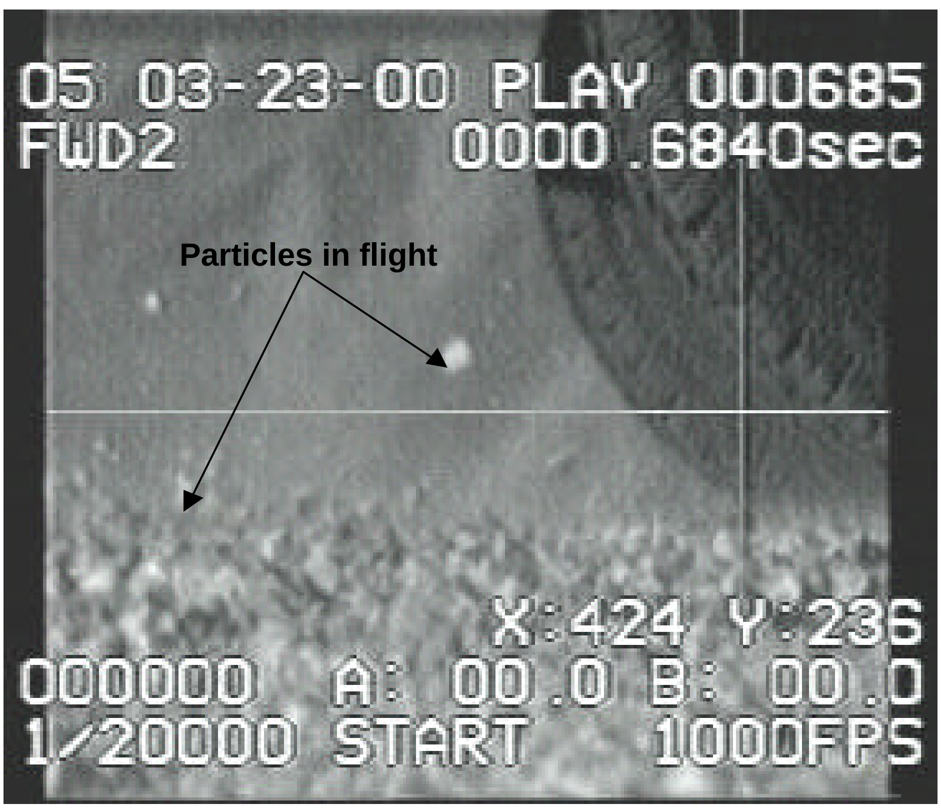


Figure 6.6.3 A Screen Shot from Stationary Camera Test

Table 6.6.1 Road Test Schedule with Camera Mounted on Truck

Test #	ID #	Grain Size	Velocity (mph)		Shutter Speed	Comments
			I	F		
1	10	C	0	15	1/20,000	W/plywood
2	9	CMF	25	35	1/20,000	W/plywood
3	3	CMF	40	40	1/20,000	W/o plywood
4	4	CMF	50	50	1/20,000	W/o plywood
5	5	CMF	60	60	1/20,000	W/o plywood
6	6	CMF	40	40	1/20,000	W/o plywood
7	1	CMF	60	60	1/20,000	W/o plywood
8	2				1/20,000	CALIBRATION
9	7	CMF	60	60	1/20,000	W/plywood
10	8	CMF	50	50	1/20,000	W/plywood

Table 6.6.2 Test Schedule with Stationary Camera

Test #	ID #	Grain Size	Velocity (mph)		Shutter Speed	Comments
			I	F		
1	9	C	0		1/20,000	Starts from the right
2	6	C	25	25	1/20,000	
3	1	C	40	40	1/20,000	
4	3	C	50	50	1/20,000	
5	4	C	60	60	1/20,000	BAD TEST
6	2	C				CALIBRATION
7	5	C	55	55	1/20,000	
8	7	C	15	15	1/20,000	
9	10	C	0		1/20,000	Starts from the center

6.7 Conclusions

The finite element analysis and road tests were conducted to examine the initiation of the particle projectile motion and its mechanism. The following conclusions were drawn:

- The finite element analysis provides an insight into the mechanism of particle projectile motion. It reveals that a particle moves vertically at a velocity and peak height depending on the properties of rock, tire and pavement.
- The Kodak high-speed digital camera is an effective tool for capturing the particle images in flight. The images can be used to calculate the particle velocity and trajectory.

7. Windshield Damage Survey

7.1 Introduction

The University of Colorado at Denver Sanding Research Team surveyed the windshields of over 400 hundred cars in two different communities in order to determine the range of damage that sand debris inflicts on commuter vehicles. The objective of Chapter 7 is to determine if there is correlation between the CDOT sanding practice and the severity and frequency of windshield damage. The vehicles surveyed were categorized with different suites of measurements. The primary categorization of the vehicles was into high and low profile (height classification statistics can be located in Appendix D). The vehicles were then categorized with respect to the following measurements:

1. The distance from the top of the windshield to the ground.
2. The distance from the bottom of the windshield to the ground.
3. The distance from the front bumper to the top of the windshield.
4. The distance from the front bumper to the bottom of the windshield.
5. The distance from the ground to the top of the front of the hood.
6. The angle of the windshield.

Figure 7.1.1 illustrates the measurements obtained in the survey and Appendix D contains a sample form for the field vehicle measurements.

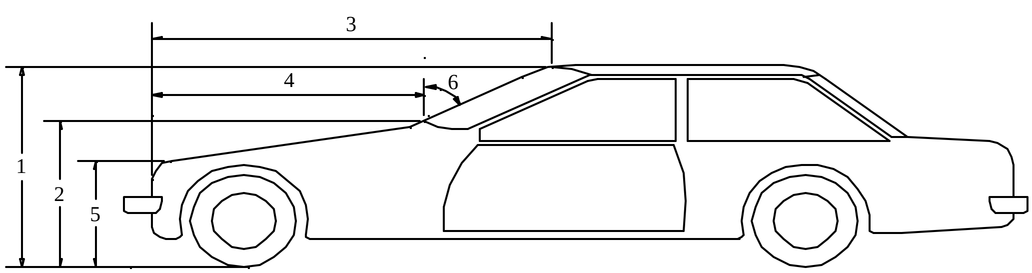


Figure 7.1.1 Illustration of Car Dimensions Obtained in the Survey

The specific damage characteristics to each windshield were recorded once the vehicles were classified. Each windshield was measured horizontally and vertically. Each apparent impact damage was recorded with respect to the lower corner on the passenger side of the car. The windshield dimensions (vertical and horizontal) were measured in order to normalize the data for comparison, Figure 7.1.2. Three impact morphologies were identified in order to categorize the damage inflicted on each windshield: Craters, Figure 7.1.3, Spiders, Figure 7.1.4, and Chips, Figure 7.1.5.

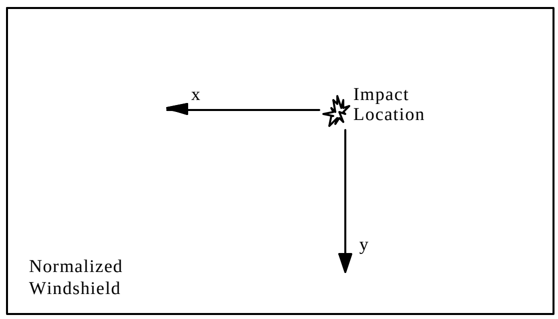


Figure 7.1.2 - Windshield Impact Dimensions

After the completion of surveys, the locations of windshield damages were normalized with the origin at the lower corner of the passenger side for the purpose of finding damage patterns and the overall central impact location. After normalization, all windshields have the unit-less dimension of 1x1. The x coordinate of the impact point is divided by the dimension of the windshield in the x direction to obtain the dimensionless x coordinate. Similarly the y coordinate is also normalized. The normalized damage locations were entered into the AutoCAD for a graphical summary. The windshield damage was grouped by four different factors on the AutoCAD graph:

1. Windshield angle
2. Distance from the front of the car to the bottom of the windshield
3. Profile (high or low)
4. Type of damage (crater, spider or chip)

Each impact point was entered onto a layer on AutoCAD based on the above groupings to enhance the visual comparison of the impact location.

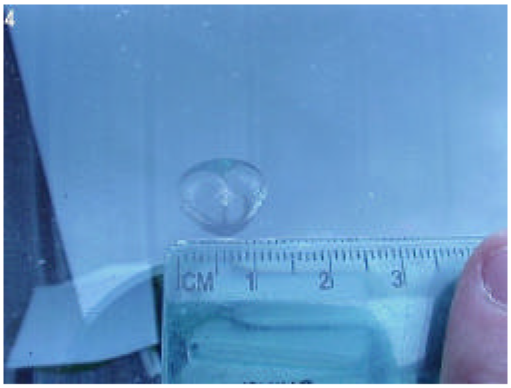


Figure 7.1.3 – "Crater" Impact

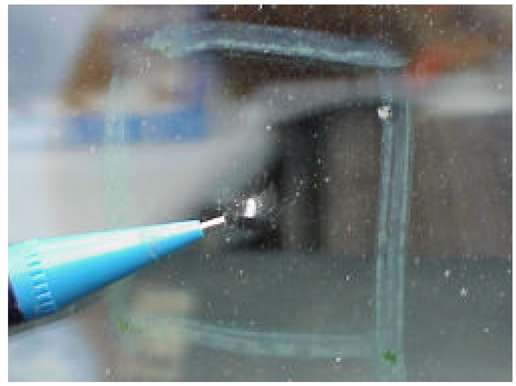


Figure 7.1.4 – "Chip"Impact

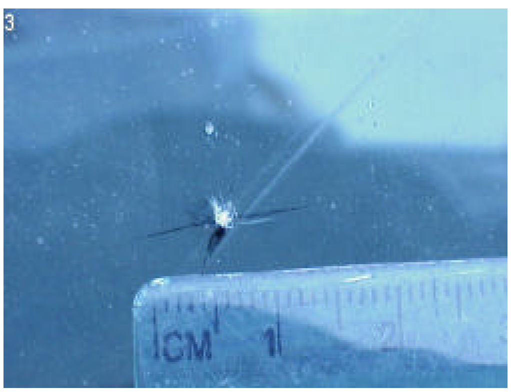


Figure 7.1.5 – "Spider" Impact

7.2 Vehicles Surveyed in Denver

The first survey took place on the Auraria campus just west of downtown. The campus houses three different colleges, and has enrollees who commute from everywhere from Denver and the Denver suburbs, to farming communities east of Denver and mountain towns. Of all cars surveyed at Auraria, 65.9% exhibited windshield damage. Table 7.2.1 contains the statistics from the 123 vehicles surveyed on Auraria. Part II of the survey of

Auraria campus vehicles incorporated a distinction between high- and low-profile vehicles. The statistics obtained can be found in Table 7.2.2. For high-profile vehicles the windshield angle (parameter 6) ranges from 25° to 45°, and the bumper-windshield distance (parameter 4) ranges from 40 and 60 inches, as shown in Figure 7.1.1.

Table 7.2.1 Auraria Survey I

	No. Surveyed	No. Damaged	No. of Impact Points	Average No. of Impact Points	$x_{average}$ Impact	$y_{average}$ Impact
All Vehicles	187	123	272	2.21	0.499	0.449
High Profile	-	42	104	2.48	0.503	0.458
Low Profile	-	81	168	2.07	0.497	0.443

Table 7.2.2 Auraria Survey II

	No. Surveyed	No. Damaged	% Damaged
All Vehicles	130	87	66.9
High Profile	36	25	69.4
Low Profile	94	62	65.9

7.3 Vehicles Surveyed in Greeley

The second part of the windshield survey took place at an office parking lot in Greeley, Colorado. Greeley is mostly a farming community. It is assumed that most people working in the office in Greeley commute from around Greeley and the surrounding rural community. Of all cars surveyed in Greeley, 48.8% had incurred damage by flying sand particles. Table 7.3.1 shows the statistics found in the Greeley study. For high-profile vehicles the windshield angle ranges from 25^o to 60^o, and the bumper-windshield angle ranges from 30 to 60 inches. For low-profile vehicles, the windshield angle ranges from 25^o to 45^o, and the bumper-windshield distance ranges from 35 to 60 inches. The damage arrays of a normalized windshield are illustrated in Figures 7.4.1 and 7.4.2, respectively.

Table 7.3.1 Greeley Survey

	No. Surveyed	No. Damaged	No. of Impact Points	Average No. Of Impact Points	$x_{average}$ Impact	$y_{average}$ Impact
All Vehicles	160	78	167	2.14	0490	0.422
High Profile	-	28	67	2.39	0.477	0.405
Low Profile	-	50	100	2.00	0.500	0.433

Table 7.4.1 Combined Statistics from all Three Sites

	No. Surveyed	No. Damaged	No. of Impact Points	Average No. of Impact Points	$x_{average}$ Impact	$y_{average}$ Impact
All Vehicles	347	201 (57.9%)	439	2.18	0.495	0.438
High Profile	-	70	171	2.44	0.490	0.435
Low Profile	-	131	268	2.04	0.498	0.439

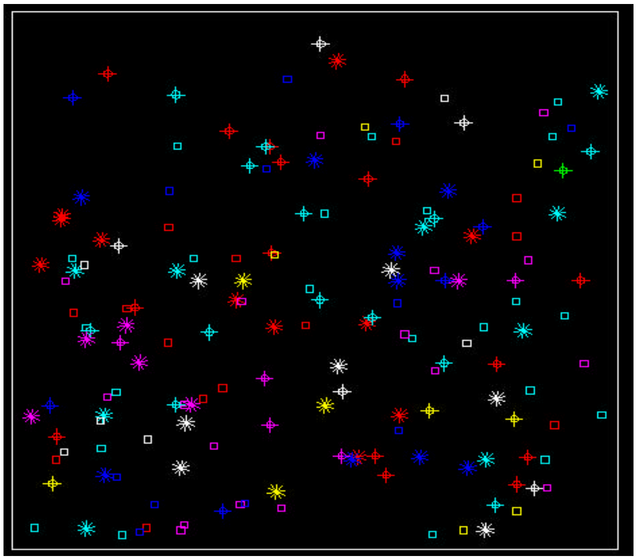


Figure 7.4.1 Windshield Damage Array for High-Profile Vehicles

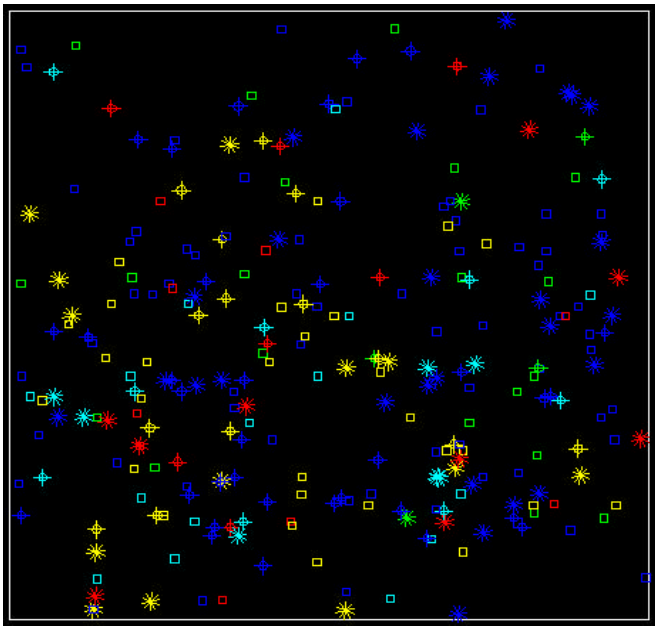


Figure 7.4.2 Windshield Damage Array for Low-Profile Vehicles

7.4 Discussion, Summary and Conclusions

The combination of the data from all three locations surveyed is indicative of a representative commuter population in Colorado. Table 7.4.1 shows the combined statistics. It was found that, of the 347 cars surveyed, 57.9% experienced windshield damage. Since the survey was conducted between the months of November 1999 and March 2000, it can be assumed that the survey result is representative of the percentage of damage incurred by commuter vehicles because the insurance statistics indicate that the majority of commuters replaced their damaged windshields after March when less damage occurs afterward. Tables 7.2.1, 7.3.1, and 7.4.1 show that high-profile vehicles tend to accrue more damage than low-profile vehicles based on the average number of impact points per windshield. This observation is further supported by the statistics in Table 7.2.2.

Cars surveyed on the Auraria Campus showed a 65.9 % damage rate compared with a 48.8% damage rate of vehicles surveyed in the Greeley parking lot. The reason for this difference is unclear, but it could be due to a number of factors. Denver and Greeley fall in different regions of CDOT and the different windshield damage rate could reflect the differences in winter roadway maintenance practice. The Denver survey was conducted on the Auraria campus and the Greeley survey was conducted on the parking lot of an auto insurance company. Students may not be as likely to replace their windshields as quickly as insurance company employees.

The center of all impact locations “x” in all categories indicates that the damage tends to center in the lower quadrant on the passenger side of the windshield. The right side of the roadway is closer to the outer lane. Traffic statistics indicate that the outer lane of a multilane highway tends to experience heaviest traffic. Besides, the residual sand tends to cumulate on the roadside. Thus, the observed damage locations could have resulted from the above-mentioned factors.

It seems deductively reasonable that x coordinate of the central impact location is nearly independent of vehicle geometry, while the y location is affected by the vehicle geometry specified by the six geometric characteristic factors of vehicle windshields. The close examination of the y coordinate of the impact point reveals that the central impact point is located, for all vehicles, on the lower half of the windshield. The impact point also tends to be proportionately higher in the low-profile vehicles and lower in the high-profile vehicles. Appendix E contains AutoCAD drawings of damages on the normalized windshield, and the frequency and locations of damage at five-degree increment of the windshield angle.

In conclusion, the windshield damage survey revealed the significant influence of winter roadway maintenance practice on the frequency and severity of windshield damage. This is both costly and hazardous to the traveling public particularly when flying rocks are large and rounded. While it is impractical to eliminate the use of sand because of the inclement winter weather conditions, its minimization is certainly desirable. In order to maintain highway safety and reduce the cost to the traveling public in the area of windshield damage, it is most critical to develop an optimal winter roadway maintenance strategy with an optimal combined use of sand and deicing chemicals. Besides, it is important to study the appropriate type, shape and size, etc of sand used in sanding.

The survey statistics also reveal that the high-profile vehicles suffer more damage than the low-profile ones and the damage is more likely in the lower quadrant on the passenger side. The windshield damage usually comes in the shape of chip, spider, and crater.

8. Windshield Damage Characteristics: Analysis and Field Tests

8.1 Scope of Analysis

Analysis of damage to windshields due to impact of a flying particle (low mass and low velocity as compared to the flying meteoroid) fits uniquely under the auspices of impact cratering and, in particular, cratering produced by the impact of sand particles produced by the traveling vehicles. Impact cratering has been widely studied by planetary astronomers, geophysicists, and, of course, ballistic scientists on the role of impact on military vehicles. Impact cratering has been recognized as a field of study for only the last few decades. The process itself and its results have been known for far longer. The area of scientific activity that contributed to our modern understanding of cratering processes is both very recent and poorly documented. Explosion craters have long been known in a military context, but until the beginning of the 20th century they were not studied in any systematic or scientific manner. Military pressures of World War II, however, brought explosion craters under scientific scrutiny. Subsequent concern over the effects of nuclear weapons fueled a large and continuing effort to understand the physics of explosive cratering. Low velocity impacts and the cratering processes that resulted from them also evolved from these studies.

It is believed that the subject of impact cratering has not been applied to the problem of damage to windshields resulting from impact of sand and other particles kicked up nearby traveling vehicles. The process of how highway sand particles are ejected from tires from nearby or passing vehicles has been discussed at length in Chapter 6. In this chapter, investigated in detail, are the processes as to how windshield damage can result from the impact of small flying particles of differing sizes, shapes and compositions and the damage patterns resulting from these impacts. First, the physical process involved in the cratering process is briefly investigated.

8.2 Fracture Mechanics Investigation of Low Velocity Impacts

8.2.1 Introduction

An understanding of the process of impact cratering requires a basic knowledge of how stress waves originate, propagate, and decay. The initial impulse is imposed on the target in terms of stress waves of varying strength and direction of motion. The shape of the resulting crater and the stress fractures radiating outward from the impact zone are critically dependent upon the characteristics of the stress wave. This section treats the aspects of stress waves in solids that are most important in particle-windshield impact on highway vehicles. The description, for reasons of simplicity, is one-dimensional. Spherically expanding waves are discussed briefly.

8.2.2 Weak Stress Waves in Solids

8.2.2.1 Elastic Waves

Elastic waves are more complex than pressure waves in liquids and gases because, unlike gases or liquids, elastic materials can support differential stresses. Stress waves in homogeneous solids are of two principal types: longitudinal and transverse. Longitudinal waves are similar to pressure waves in fluids; transverse waves have no analog in fluids. Transverse waves arise because solids, besides resisting compression, also resist change in shape or distortion. This resistance is expressed by the shear modulus, G, which is almost always smaller than the bulk modulus K_0. Transverse waves thus travel more slowly than longitudinal waves.

These waves are called “transverse” because the direction of motion of a small area of the solid accelerated by the wave is perpendicular to the direction of wave propagation. There are actually two independent transverse waves whose particle velocity vectors are orthogonal to one another while both are perpendicular to the wave propagation direction.

Both transverse waves travel at the same speed in homogeneous solids, but they are reflected with different amplitudes from interfaces between different substances or from free surfaces. They may travel at different speeds in anisotropic materials.

Elastic waves are described by linear equations. The equations are written in terms of the particle velocity vector, whose three components can describe the full panoply of stress waves in solids. In one dimension (for a wave of infinite extent perpendicular to the direction of propagation) the equations of motion are:

$$?^2u_L/?t^2 = c_L^2\ ?^2u_L/?x^2$$

$$?^2u_{T1,T2}/?t^2 = c_T^2 ?^2u_{T1,T2}/?x^2$$

where u_L is the particle velocity in a longitudinal wave that propagates at speed c_L, and u_{T1} and u_{T2} are orthogonal transverse particle velocity components that both propagate at speed c_T. The propagation speeds depend upon the bulk and shear moduli:

$$c_T = (G/?_o)^{0.5}$$

$$c_L = [(K_o + 4G/3)/?_o]^{0.5}$$

The longitudinal wave speed in a solid is greater than the transverse wave speed because the solid's resistance to distortion, parameterized by G, augments its resistance to compression, parameterized by $K_{o.}$ The transverse wave speed depends only on the shear modulus, G, because the transverse wave motion does not cause a change in the volume of the material it passes through. The stress state in an elastic wave must be described by a number of different stress components in addition to the pressure. Longitudinal stresses, transverse stresses, and shear stresses collectively form the components of a stress tensor. Even in a plane longitudinal wave, the stress must be represented by a tensor, since it involves both distortion and compression, making the stress components parallel and perpendicular to the direction of propagation unequal. These stresses are given by the equations

$$\sigma_L = -\rho_o u_L c_L$$

$$\sigma_P = [\nu/(1 - \nu)]\sigma_L$$

where σ_L is the longitudinal stress, σ_p is the stress component perpendicular to the propagation direction, and ν is Poisson's ratio given by

$$\nu = 0.5(3K_o - 2G)/(3K_o + G)$$

The minus sign for the longitudinal stress in the above equation is because the engineering sign convention is used in which tensile stresses are positive and compressive stresses are negative. The stress in the transverse wave is pure shear with the shear stress

$$\sigma_S = \rho_o u_T c_T$$

The magnitude of the stress in a transverse wave is generally less than that in a longitudinal wave, given similar particle velocities, because the transverse wave speed is generally smaller than the longitudinal wave speed.

The energy density in either of these wave types is the sum of the mean kinetic and distortional energies over a wave cycle. A fraction of the energy imparted by an impact is ultimately carried away by longitudinal and transverse waves. In some cases this energy can be refocused in regions distant from the impact site and can cause fracture there. The phenomenon is noticed in the field windshield impact tests.

Transverse waves as well as surface waves have been observed to be of minor importance for the cratering process in impact sites mainly because the strength of such waves is limited by the shear strength of the material. Often the stresses developed during the very early stage of an impact are so much greater than the strength of materials that transverse waves may be neglected. This approximation fails during the later stages of crater excavation but may not have much effect on the shape of the final crater.

8.2.2.2 Reflection of Elastic waves at Interfaces and Free Surfaces

Impact craters are observed to form near the free surface of targets that are often composed of layers of contrasting elastic properties. Safety glass is a good example where a layer of plastic film is interposed between two layers of glass. The interaction of impact-generated stress waves with free surfaces and interfaces is an important part of the cratering process. This interaction can be treated exactly only for linear waves but the concepts developed are quite useful in understanding the process as to how cratering occurs and the fractures generated from the impact away from the crater. Reinhart (1960) discussed this process clearly. It is briefly discussed in this section. In what follows, the major concept necessary for the understanding of cratering process as related to windshield damage is described. Only the linear longitudinal wave is discussed.

Reflection at interfaces is particularly simple in elastic waves because they are linear: the stress or particle velocity in an area affected by two such waves is a component-by-component sum of the stresses or particle velocities of each wave. This is true only for very low amplitude waves in homogeneous isotropic media. Both of these conditions are met in the low velocity impact of windshields by rock particles.

Any wave, elastic or not, that impinges on an interface where material properties change suddenly, such as the plastic separating two glass sheets (safety glass), must preserve the continuity of certain physical quantities. Thus, the mutual impenetrability of solids at contact requires the same particle velocity in the adjacent substances. An obvious exception occurs if a crack opens at an interface under extension. Similarly, the absence of external forces at a contact requires continuous stresses, both normal and shear, across the contact surface. These boundary conditions are satisfied by the creation or modification of elastic waves at the contact. Figure 8.2.1 illustrates a rectangular compressive pulse approaching a free surface, and its reflection as a tensional pulse. By definition, a free surface cannot support normal or shear stresses.

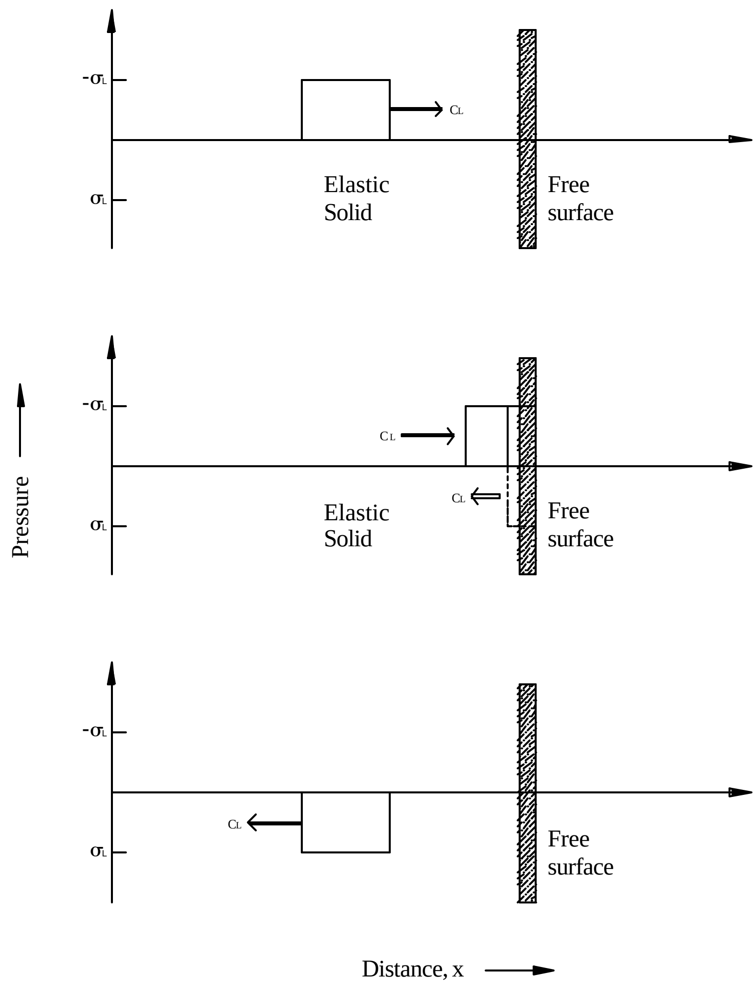


Figure 8.2.1 Elastic Longitudinal Wave Propagation

When a pulse strikes the free surface, a new elastic wave is created, maintaining the normal stress at zero. Because elastic waves in one dimension must travel either to the right or left with speed c_L, and because a rightward moving pulse generated at the surface could not influence the stress in the elastic medium, a leftward moving pulse therefore arises at the surface. The zero normal stress boundary condition requires a tensional pulse, so that the sum of the longitudinal stress σ_L in the two pulses is zero. Once generated at the boundary, the tensile pulse propagates to the left without modification because there is no other source of elastic waves in the medium. The rightward moving tensile pulse overlaps with the leftward moving tensile wave for a short period of time. This gives rise to a locally complex stress condition. Since the waves are linear the net stress is merely the sum of the stresses in the two pulses at any given time.

Although the normal stress must vanish on a free surface, the particle velocity does not. The medium to the right of the elastic medium offers no resistance to its motion and the resulting velocity is the sum of the particle velocities of both the compressive and tensile pulses. The particle velocity in the compressive pulse, given by the equation $\sigma_L = -\rho_o u_L c_L$, is u_L and the particle velocity in the tensile pulse, however, is also u_L to the right because of the sign reversal for both the stress and the direction of motion. The net particle velocity during the time that the pulses are interfering is thus $2u_L$ to the right, which is known as the velocity-doubling rule. The particle velocity at the free surface is approximately twice that in the incident pulse even for strong high amplitude stress waves. At one time this rule formed the basis of a technique for measuring particle velocities. Here fragments, called spalls, often break off near the free surface. The velocity of these spalls is roughly twice the particle velocity in the original compressive pulse, which is inferred from the spall velocity by dividing it by two.

Figures 8.2.2 and 8.2.3 illustrate the interaction of a compressive rectangular pulse moving to the right with (b), an interface where the wave velocity is smaller on the right than on the left, and (c), an interface where the velocity is larger on the right. Case (b) is similar to wave reflection at a free surface, except that the continuity of particle velocity as well as normal stress across the contact requires the creation of a third pulse, a rightward moving compressive pulse that travels into the elastic material to the right of

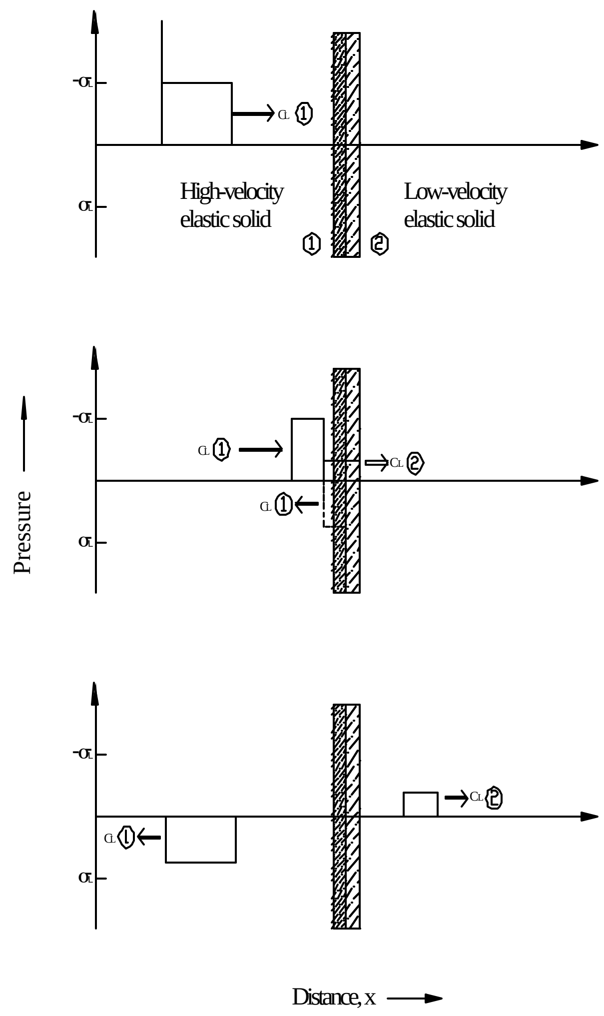


Figure 8.2.2 Compressional Impulse (Case b)

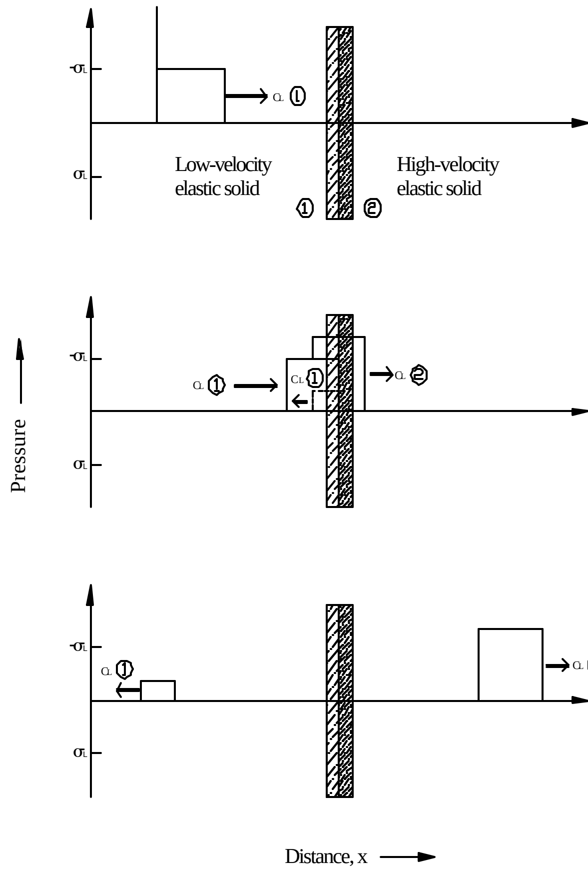


Figure 8.2.3 Compressional Impulse (Case c)

the interface. A tensile pulse is still reflected into the medium at the left. Because the energy of the original pulse is now divided between the transmitted compressive pulse and the reflected tensile pulse, the reflected pulse is less intense than it was when the contact was a free surface.

In the case when the pulse travels across an interface from a low sound velocity medium into a high sound velocity medium, it behaves much like a pulse produced by an impact on a safety windshield propagating across the low sound velocity insert into the higher sound velocity in glass. As before, there is a transmitted wave and a reflected wave, but both velocities are compressive. Because of the infinite sound velocity to the right, the interface approximates a rigid wall with zero velocity that perfectly reflects the incident wave. The maximum stress is thus twice that of the incident pulse.

The examples described so far deal with the behavior of a rectangular compressive pulse. The same results apply to any pulse shape or sign. Thus, a triangular compressive pulse moving to the right toward a free surface is reflected as a triangular tensional pulse traveling to the left. The pulse shape is preserved because the stress in the original pulse must be canceled at the free surface at all times. Only a tensional pulse of precisely the same shape as the original is capable of this. Analogous results hold for the other cases where the interface is not a free surface. In the following sections, the above wave propagation principle is applied to the damage assessment to windshields subjected to low velocity impact from particles kicked up by the nearby vehicle.

8.3 Field Tests for Windshield Damage

8.3.1 Introduction

As mentioned in Section 5, the following factors influence the windshield damage upon impact with granular particle: particle shape, mass, hardness, incident angle and velocity. This section attempts to assess the effect of the above-mentioned parameters on the windshield damage severity defined as the type of fracture, superficial or penetrating. Superficial damage is a minor scratch of the surface of the windshield, whereas a penetrating fracture is a severe damage, which can cause further fracture propagation due to thermal effects. To develop the correlation between the damage severity and the influencing particle characteristics, two series of tests, Test A and Test B, were performed. The high-speed camera was used to record the particle incident and exit trajectories from which incident and exit velocities are calculated. The particle shape, size, mass, and type were recorded before the test.

8.3.2 Impact Test A

Field Impact Test A series was conducted on several test vehicles donated by the Klode Salvage Distribution Center in Littleton, CO. The vehicles included a Mercedes, a cargo Van, and two compact cars as shown in Fig. 8.3.1. The rock samples were collected from a local gravel distributor, and were hand chosen to include rocks of different material types. The size ranged from 1/2" to 1" diameter. Both angular and rounded rocks were chosen. The types of rock included Lava Rock, River Rock (conglomerates), Granite, Sandstone, and Gneiss as shown in Fig. 8.3.1. Particle weight ranged from 3 to 12 grams.

a) Particle release

b) Setting up for the shot

Figure 8.3.1 Impact Test A Site Location

a) River rock sample used in Test A

b) Gneiss sample used in Test A

c) Lava Rock sample used in Test A

d) Quartz sample used in Test A

e) Dolomite sample used in Test A

Figure 8.3.2 Test Samples Used to Determine the Extent of Damage When Impacted with Windshield. Varieties of Rock Types Were Chosen for Damage Comparison

From a position perpendicular to the line of travel, the impact was filmed at one thousand frames per second. This allows the motion playback through the period of impact. The exact particle release time and the location of the impact were critical components in the effort to capture a good image via the high-speed camera. Each shot was rehearsed in order to identify the exact location of impact. The precise location of the rock-windshield impact point allows the proper camera focus before the actual test is carried out. Holding its extension constant at Hole #10 held the slingshot force constant. Velocity of ¾" lava rock was calculated using two high-speed camera images as follows:

First, the displacement, Δd, between two separate locations of the rock as follows:

The particle coordinates at two locations are:

$X_1 = 301$ $\quad\quad\quad$ $Y_1 = 184$

$X_2 = 268$ $\quad\quad\quad$ $Y_2 = 223$

The coordinate change are: $\Delta X = 33$ pixels; $\Delta Y = 39$ pixels.

Thus, the distance of the particle between the two selected frames is:

$$\Rightarrow \Delta d = \sqrt{\Delta X^2 + \Delta Y^2}$$

$$\Rightarrow \Delta d = \sqrt{33^2 + 39^2} = 51.09 \text{ pixels}$$

Distance Calibration:

$$WhiteTape = 12mm = 40\, pixels$$

$$12mm/40\, pixels = 0.3\, mm/pixel$$

Δd = *51.09 pixels = 51.09 x 0.3mm/pixel =15.33 mm*

Velocity Calculation:

$V = \Delta d / \Delta t$ = 15.33 mm / 0.005 sec

= **6.86** *miles/hour*

Approximately 20 tests were conducted and recorded. The results were consistent for the rock samples of size 1/2" and greater with highly pronounced damage. Two main categories of penetrating fractures can occur with impact of particle sizes between 1/4" to 1/2". The first type is what is often referred to as a "bull's-eye" fracture by the research team, where a series of concentric fracture rings form about the point of impact, Fig. 8.3.3. The second type is a "star" fracture (or spider fracture), Fig. 8.3.4, with a group of cracks radiated from the point of impact. The radial cracks are approximately 1/4" to 1/2" in length and range in number from three to six. The surface of the glass at the center of impact is disintegrated.

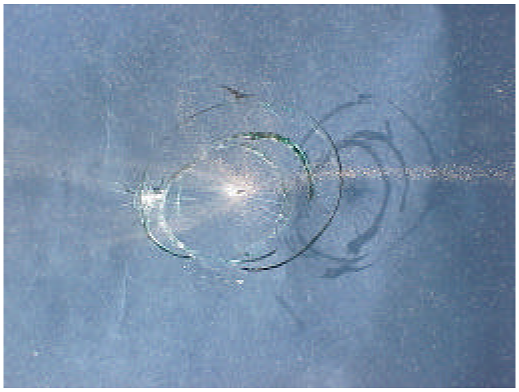


Figure 8.3.3 Concentric Ring Fracture "Bull's-Eye" from Particle Impact

Figure 8.3.4 Radial Crack Fracture "Star" from Particle Impact

8.3.3 Impact Test Series B

Test Series A produced significant results regarding the damage to a windshield caused by angular shapes and rounded shaped rocks. The results showed that rocks larger than 1/2 inch produced considerably large fractures of both patterns. However, in the Test Series A, no effort was paid to securing the test rocks used in the Colorado sanding practice. Thus, Test Series B was performed using the CDOT sand in an attempt to determine the degree of severity of CDOT sand on windshield damage.

Test Series B used the actual sand particles from Region 1, Aurora. The slingshot device was used to generate the particle velocity ranging from 50 to 70 mph by holding its elastic deformation at a required constant value. The particle trajectory is held horizontal with the windshield angle of 35 degrees. Eight 20-gram samples of sand mix from Aurora region were obtained for the tests. The size, shape, and weight distributions of the chosen sand particles were similar. All samples were oven dried to evaluate their respective moisture content. The moisture content was found to be negligible. Particles were coated with a thin impermeable film, the dimensions along major and minor axes measured using a caliper, classified into three different sizes: small, medium and large, and also classified into rounded, subrounded and subangular based on the dimensions of the major and minor axes, Fig. 8.3.6. To evaluate sample volume, each of the eight sample groups was submerged in a graduated flask filled with a known volume of water to measure its volume by the volume of water displaced by sample submergence. The density of the sample was then obtained by dividing the weight by its volume. The above particle characteristics are recorded in Table 8.3.1.

a) Medium sample used on test track.

B) Aurora mix used in Test Series B.

Figure 8.3.5 Aurora Mix Used in the Road and Impact Tests

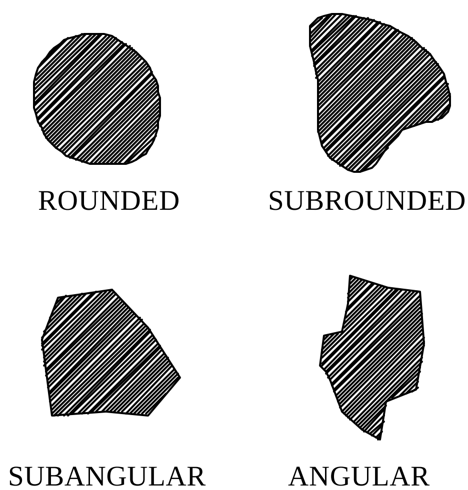


Fig. 8.3.6 Particle Shape Classification

Table 8.3.1 Test Series B Data

LABORATORY PARTICLE IMPACT TESTS

(Particle Characteristic)

Particle Group (density gm/cc)	General Size	Axis		Roundness Classification	Particle Mass (grams)
I (2.47)	Small	*Minor*	3.7	Rounded	0.17
		Major	8.9		
	Medium	*Minor*	6.05	Rounded	0.22
		Major	7		
	Large	*Minor*	7.25	Rounded	0.41
		Major	12.05		
II (2.52)	Small	*Minor*	4.85	Rounded	0.09
		Major	5.3		
	Medium	*Minor*	5.55	Subrounded	0.21
		Major	8		
	Large	*Minor*	7.85	Rounded	0.55
		Major	11.25		
III (2.36)	Small	*Minor*	3.4	Subrounded	0.03
		Major	4.65		
	Medium	*Minor*	4.85	Rounded	0.19
		Major	7		
	Large	*Minor*	5.75	Rounded	0.39
		Major	9.85		
IV (2.73)	Small	*Minor*	3.7	Subangular	0.08
		Major	6.5		
	Medium	*Minor*	4.25	Subangular	0.12
		Major	7.5		
	Large	*Minor*	7.75	Subangular	0.5
		Major	9		
V (2.46)	Small	*Minor*	2.3	Subrounded	0.09
		Major	6.9		
	Medium	*Minor*	4.5	Subangular	0.13
		Major	6.95		
	Large	*Minor*	7.5	Subangular	0.4
		Major	8.63		
VI (2.57)	Small	Minor	5.25	Subangular	0.14
		Major	7.25		
	Medium	Minor	5.85	Subangular	0.27
		Major	7.3		
	Large	Minor	7.6	Subrounded	0.36
		Major	9.2		
VII (2.50)	Small	Minor	4	Subangular	0.05
		Major	4.25		
	Medium	Minor	5.3	Subrounded	0.18
		Major	8.3		
	Large	Minor	8.65	Subrounded	0.65
		Major	11.2		
VIII (2.55)	Small	Minor	3.65	Subrounded	0.08
		Major	6.15		
	Medium	Minor	5	Subrounded	0.23
		Major	8.2		
	Large	Minor	10.6	Subrounded	1
		Major	11		

8.3.4 Conclusions

The slingshot is effective in simulating particle velocity and the high-speed camera in capturing the particle trajectory for velocity calculation. The severity of windshield damage depends on the size, shape, hardness mass (or density) and velocity of rock particle. The angular and dense particles caused "star" fractures that are less severe, whereas the more rounded particles caused large "bull’s-eye" shape fractures that are more severe. A small, angular particle resulted in chip fracture and the less dense Lava Rock resulted in a scattered pattern of surface chips.

9. Windshield Damage Cost and CDOT Winter Roadway Maintenance Practices

9.1 Introduction

Cost of sanding is evaluated by determining the expenses spent on both the winter roadway maintenance and the windshield repair or replacement. The expense for windshield repair or replacement, in particular, is determined based on the available claim data provided by the insurance companies that participated in the study, namely Company A and Company B, although more companies jointly funded the research. Besides the expenditure for the windshield damage repair or replacement, the number of windshield damage claims is also an important indicator. The number of claims also reflects the amount of rock particles from the winter roadway sanding and the construction debris. Since no information is available for the construction debris, the study assumes that only the sanding rocks cause the windshield damage. Cost of windshield damage due to winter roadway sanding is an extremely complex problem involving many influencing factors, and hence only qualitative conclusions could be drawn based on the processed data.

To examine the number of windshield damage claims and expenditures, the market share of the participating insurance companies is first identified. The participating insurance companies, Company A and Company B, have 24% and 8% of the automobile insurance market share in the state of Colorado, respectively. Thus, the combination of the data provided by both insurance companies reflects 32% of the total windshield damage claims and expenditures in Colorado. This statistic provides the basis for the projection of the statewide claims and cost. Figure 9.1.1 shows the automobile insurance market share distribution in Colorado.

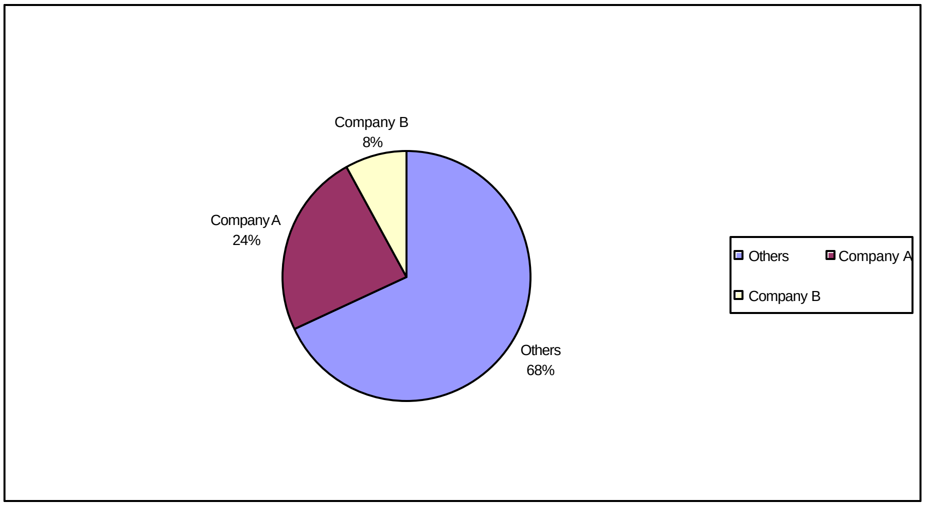


Figure 9.1.1 Market Shares of Various Insurance Companies in Colorado

9.2 Timing and Nature of the Windshield Damage Claims

From the windshield damage claim data, the claims versus time are plotted in Figure 9.2.1 from year 1997 to 1999. In general, more damaged windshields were fixed from March to August of each year than other months. Windshield damage claims occur less in the time span of September through February. Damaged windshield can either be repaired or replaced. Figure 9.2.1 also shows more windshield replacement than repair.

It must be noted that the time of windshield damage occurrence and the time of filing the damage claim do not coincide. The number of claims in a particular month does not necessarily reflect the number of windshields damaged in that month. Figure 9.2.1 shows the total number of claims and the claim-filing month. The cyclic nature of claims indicates that windshields are more likely damaged in the winter driving conditions and fixed in the summer or fall season. This delayed claim action possibly reflects the procrastinating nature of automobile owners or the desire of the owners to prevent the damage to the new windshield after its replacement or repair.

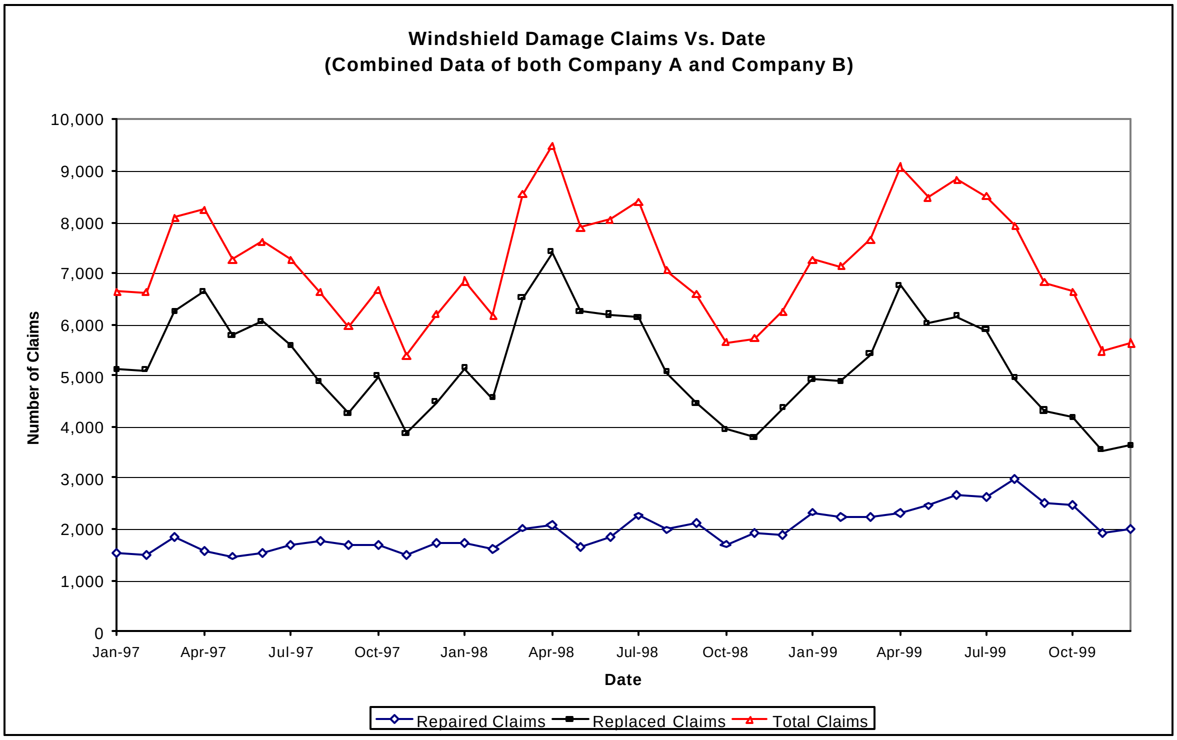


Figure 9.2.1 Windshield Damage Claims Time History

The number of automobiles has been increasing at a fast pace over the past ten years in Colorado as indicated in the policy counts provided by the two insurance companies, Figure 9.2.2. This assumes that all owners bought insurance policies, since the state law requires every automobile to be insured. The number of windshield damage claims has also increased for the past several years. To delineate the increasing or decreasing trend of the windshield damage claims, the number of windshield damage claims is normalized against the total policy counts. This process reveals the claims as percentage of the entire automobile population (or the total number of policy counts). Figure 9.2.3 shows the claims/policy-count ratio over the past eight years. The ratio has experienced about 2 to 3% annual increase, but the rate of increase has slowed down in 1998 and become negative in 1999 and 2000. The increase before 1998 indicates that an increasing percentage of insured automobile experienced and claimed windshield damage. The decrease in 1999 and 2000 indicates a decreasing percentage of insured vehicle owners claimed windshield damage. The influencing factors could include: weather conditions, sanding, driving habits, including automobile speed, of the automobile operators, number

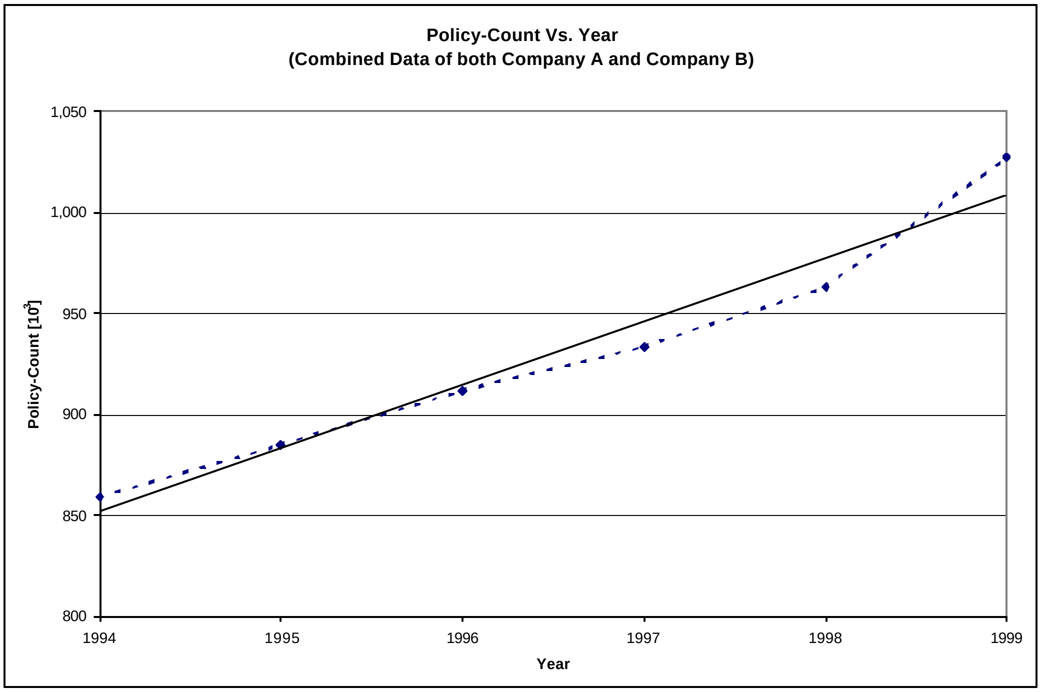


Figure 9.2.2 Policy Count Time History

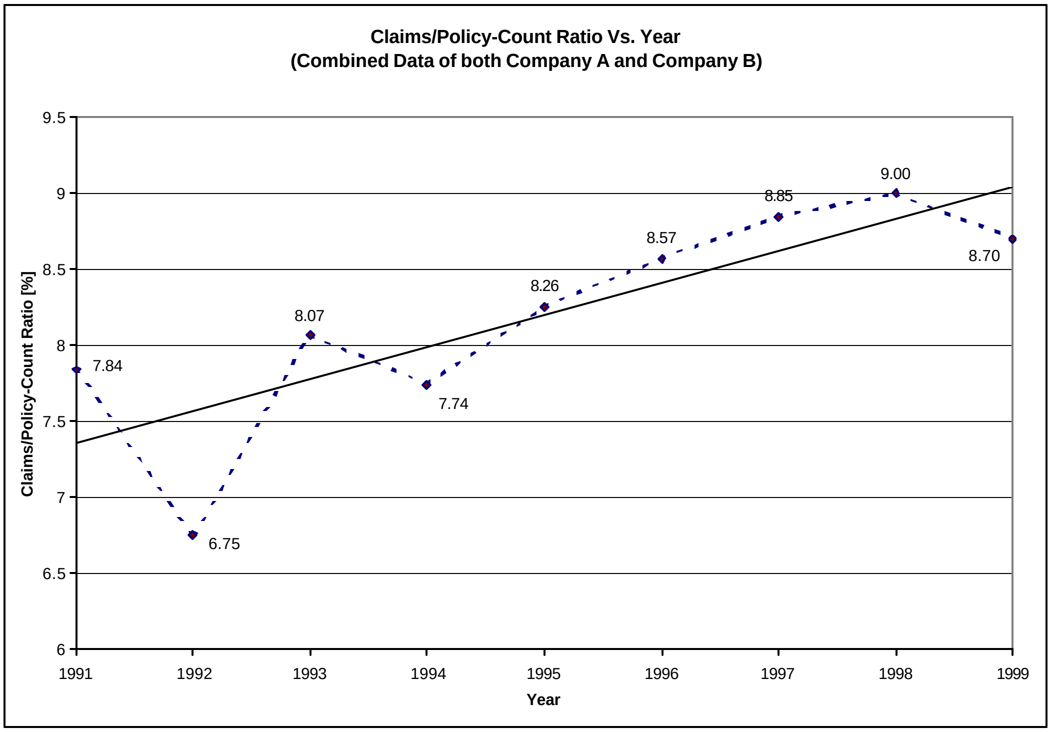


Figure 9.2.3 Claims to Policy Count Ratio Time History

of automobiles accessing roadways, average miles driven, and types of automobile. Over the surveyed period, the weather has not gotten worse, and the amount of sanding has been decreasing. Thus, sanding and weather cannot be blamed for the increasing ratio before 1998. Vehicle types, driving habits, average miles driven, and number of vehicles accessing highways are the potential causes. The decreasing rate can reflect the CDOT new policy of using less sand and more deicing chemicals.

Since 1994, to improve the air quality, particularly in the Denver metro area, CDOT and all municipalities have de-emphasized the use of sand and increased the use of de-icing chemicals as the winter roadway traction enhancement agents. During this period, Figure 9.2.1 shows the annual windshield damage claims have increased, but at a rate slower than the rate of population increase. This is mainly due to the shift of the CDOT and all municipalities from sand to deicing chemicals since 1994. The reduction in use of sand is most likely responsible for the reduction of the windshield damage cost after the population correction and naturally the insurance cost to the driving public.

It is interesting to note that the number and types of windshield damage claims can be different from one area to the other. Figures 9.2.4 and 9.2.5 show the repair and replacement claim time history for the Mile High and Frontier areas, respectively. The Mile High area includes metropolitan Denver, Boulder, and Colorado Springs. The Frontier area covers the rest of the state. By comparing Figures 9.2.4 and 9.2.5, it is evident that more damaged windshields were replaced in the Mile High area than in the Frontier area. On the other hand, more damaged windshields were repaired in the Frontier area than in the Mile High area.

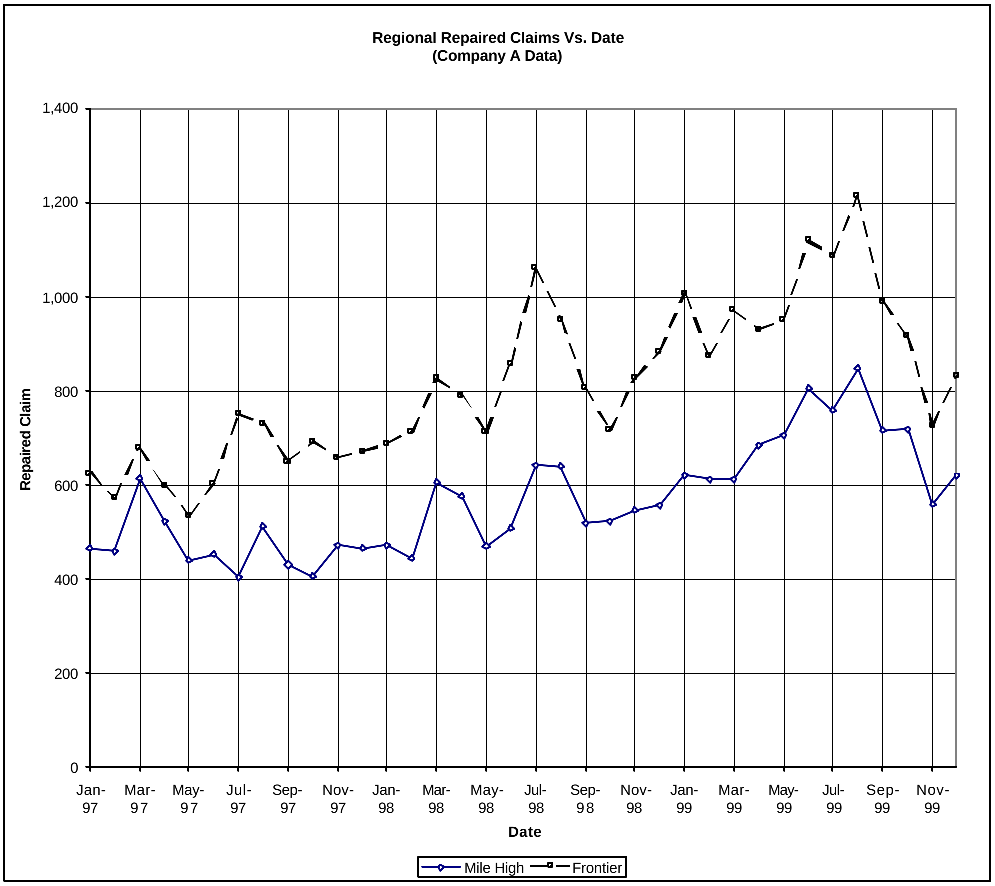


Figure 9.2.4 Repair Claims Time History per Region

As a premise, a replaced windshield is more severely damaged than a repaired one. The difference in claims for replacement and repair between the Mile High and Frontier areas can simply be the difference in driving habits and claim practices by the drivers. A high automobile density in the Mile High area could also be responsible for the trend. In high traffic density areas, more rocks are picked up and, hence, the risk of windshield damage also increases. Besides, the automobile traveling at a higher speed will increase the airborne particle velocity and, thus, cause more severe damage as demonstrated in the companion impact damage study. The impact study also concluded that a larger rock would cause more severe windshield damage than a smaller one. Besides the physical factors as described above, the criteria for windshield replacement and repair could be different for urban and rural regions.

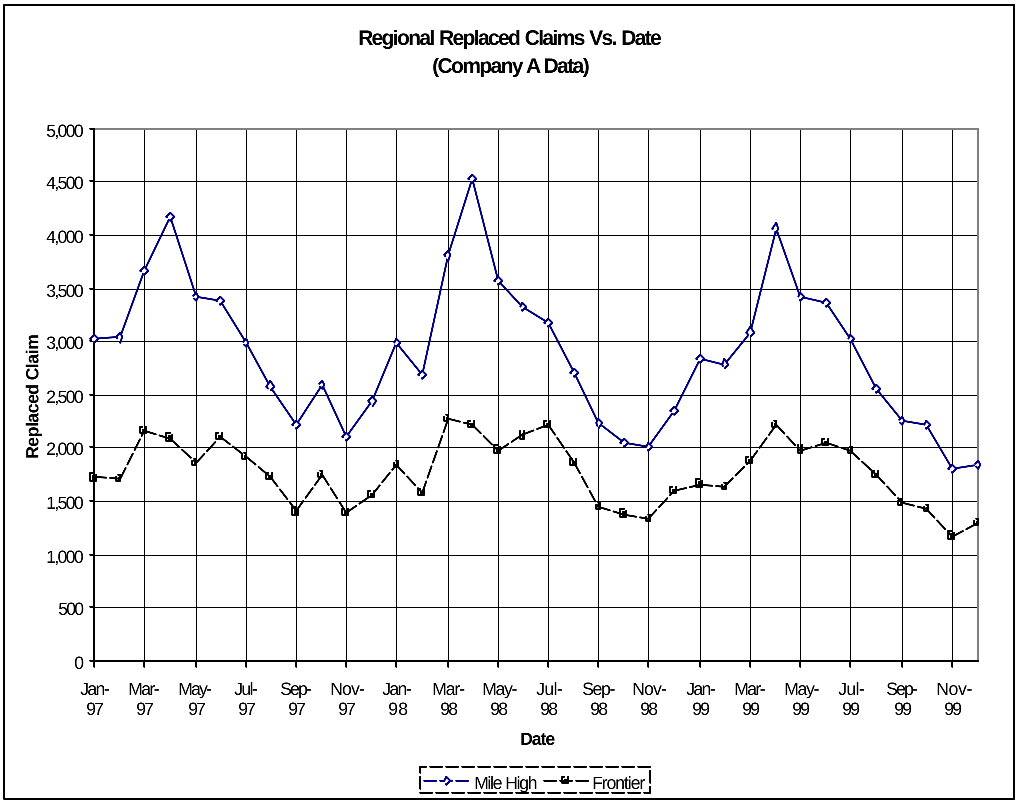


Figure 9.2.5 Replacement Claims Time History per Region

9.3 Windshield Damage Cost

The average cost for windshield repair and replacement is calculated from 1994 to 1999. Results are shown in Figure 9.3.1 and 9.3.2, respectively. It is observed that the average cost per repair or replacement has increased. The average repair cost has gone up $11 in five years, whereas the average replacement cost $95. Inflation is, at least, partially responsible for the increase. The combined cost of windshield repair and replacement from the two participating insurance companies is shown in Figure 9.3.3. Knowing the market share percentage of the two insurance companies, the statewide cost, Figure 9.3.4, can be calculated. The Colorado statewide windshield cost is estimated at $90 million for the year 2000.

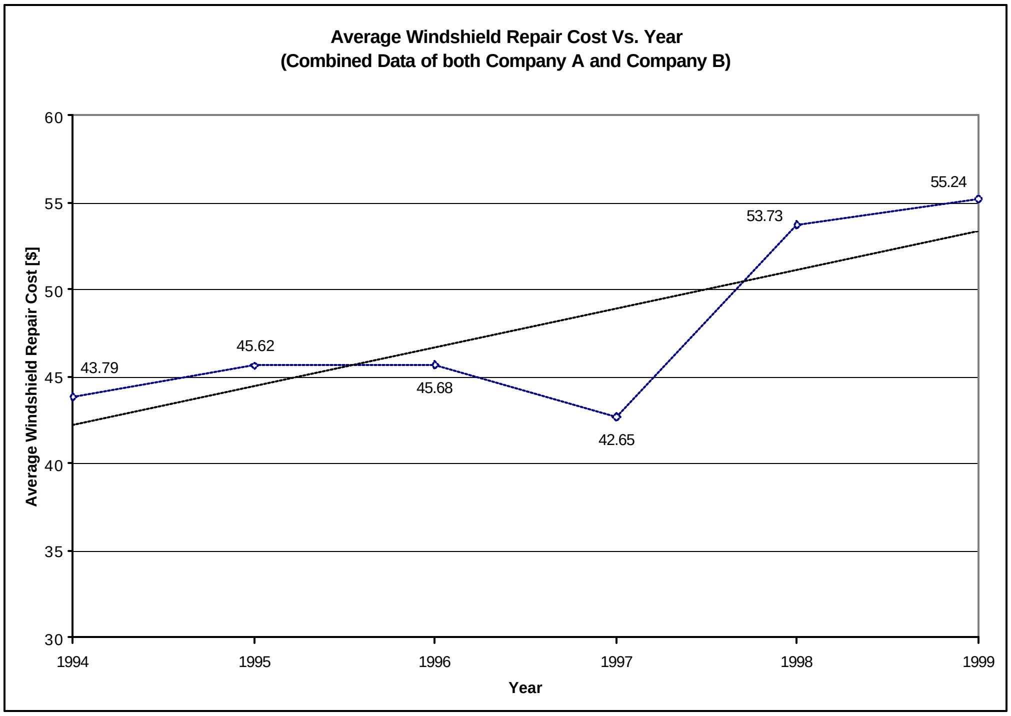


Figure 9.3.1 Average Windshield Repair Cost Time History

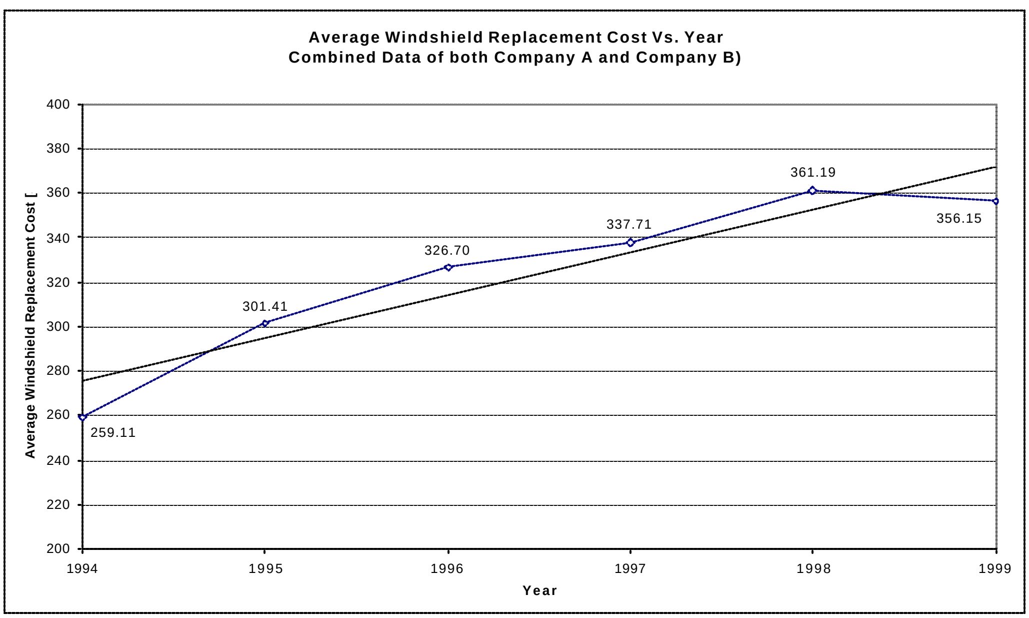


Figure 9.3.2 Average Windshield Replacement Cost Time History

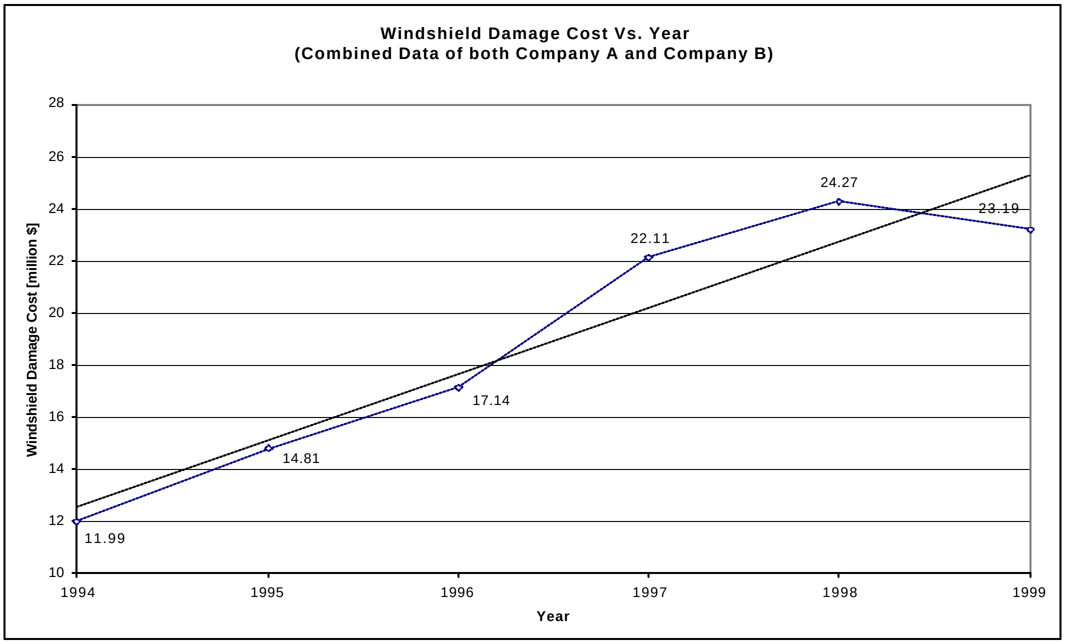


Figure 9.3.3 Windshield Damage Cost Time History Attributed to Company A and Company B

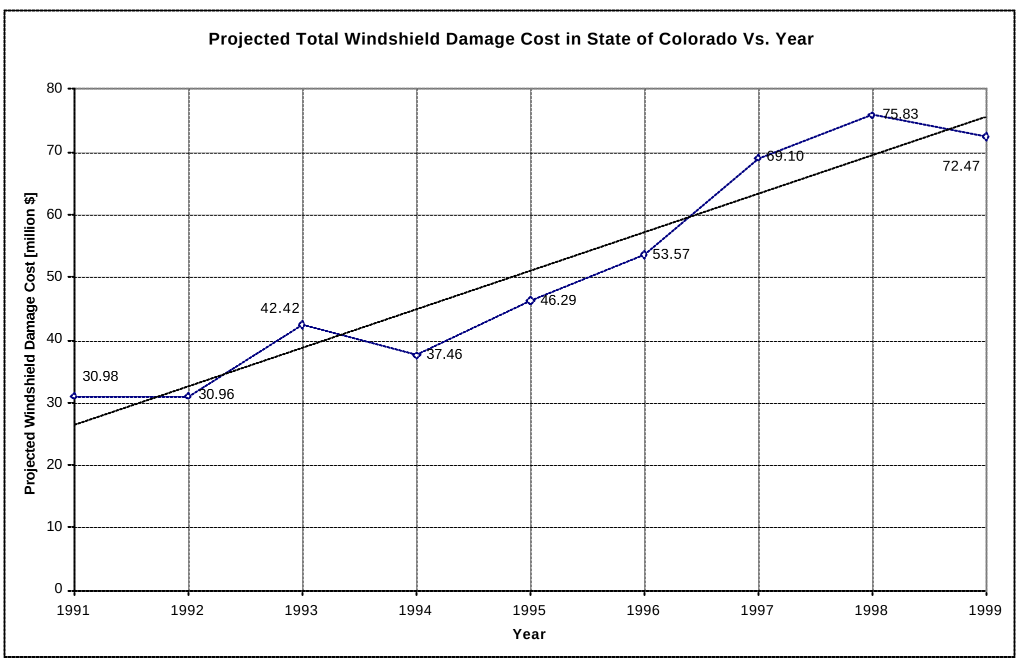


Figure 9.3.4 Projected Total Windshield Damage Cost in State of Colorado

9.4 Damage Statistics vs. CDOT Roadway Maintenance Practices

To study the effect of the shift of the CDOT winter roadway maintenance policy on the cost to the traveling public, an appropriate study period must be determined. The study period for the CDOT winter roadway maintenance practice spans a period of eight years. The insurance statistics, claims, and policy counts are not available over the entire study period. Thus, the study on the effect of the policy shift will cover only the period when the insurance statistics are available. The statistics provided by Company A and Company B constitute 32% of the total policy count in Colorado.

9.4.1 Auto Insurance Policy Counts, Claims vs. CDOT Winter Roadway Maintenance Policy Shift

Figure 9.2.2 shows the insurance policy count rose almost 20% from 1994 to 1999, 4% per year. Figure 9.4.1 shows that the policy count and the total windshield damage claim both rose about 10% from 1997 to 1999. In the same two-year period, the replacement claims were down, while the repair claims were up.

Figures 9.4.2, 9.4.3, and 9.4.4 give the historic perspective of the CDOT policy shift in the use of the traction enhancement agents. Before 1994 CDOT used almost exclusively sand, sand/salt mix and rock salt for pavement traction enhancement. To date the practice still varies from region to region. It is tailored to the needs and resource availability of the region. Starting in 1994, CDOT began its experimental use of deicing chemicals. Since then, the use of deicing chemicals has drastically increased statewide, particularly in the Grand Junction and Denver regions, with the exception of a couple of regions. Meanwhile, the use of solids has also experienced drastic decrease.

This reduction in use of solids should result in a decrease in windshield damage claims. Figure 9.4.5 shows the CDOT use of different traction enhancement agents from 1996 to 2000. It is clear from Figure 9.4.5 that the use of solid agents, especially sand, was on a downward trend. The use of sand/salt mix appears to be on a downward trend except the spike in 1999 resulting from its heavy use in the Pueblo Region due to severe weather conditions as discussed in Chapter 2. The use of deicing chemicals has increased 10 times in just four years.

The above-stated policy shift was initiated mainly to address the air quality problems in some urban areas, like Denver and Grand Junction, and some ski mountain communities. Obviously the reduction of windshield damage cost is yet another benefit of the shift. As seen in Figure 9.3.4, beginning in 1999 the windshield damage cost has been on the way down. This took place in the midst of Colorado's population increase. The Census 2000 shows that the Colorado population increased by about one million during the study period. Thus, this reduction in cost to the traveling public due to the reduction in windshield damage is at least partially attributed to the CDOT policy shift.

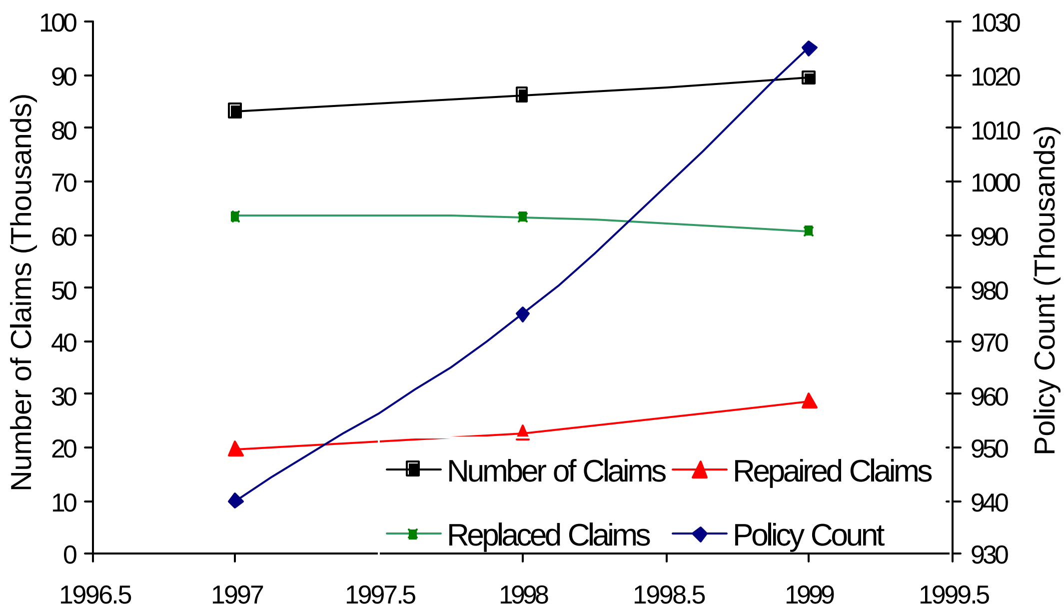


Figure 9.4.1 Policy Count and Total Claim Data

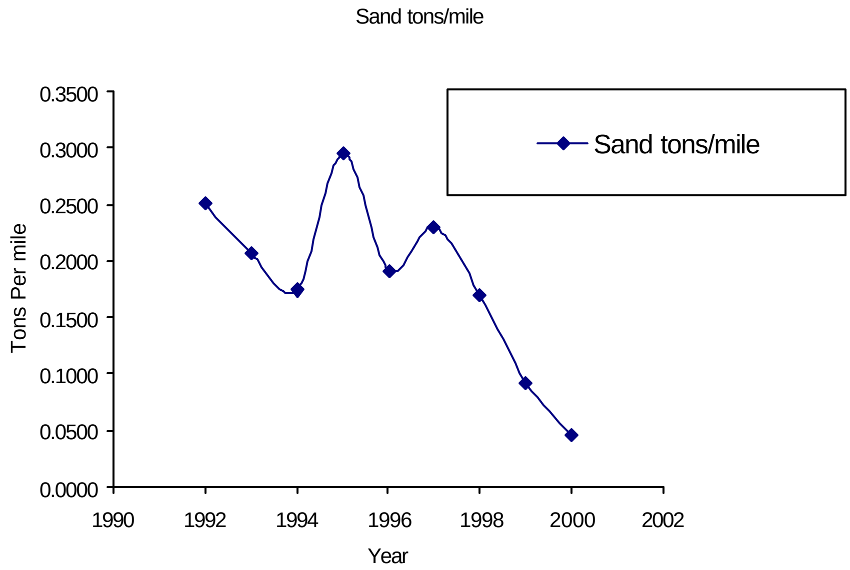


Figure 9.4.2 CDOT Trend of Sand Use for Traction Enhancement

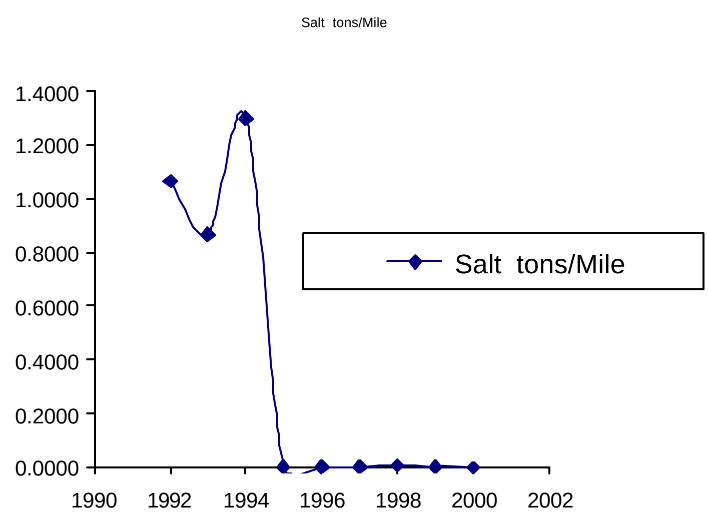


Figure 9.4.3 CDOT Trend of Salt Use for Traction Enhancement

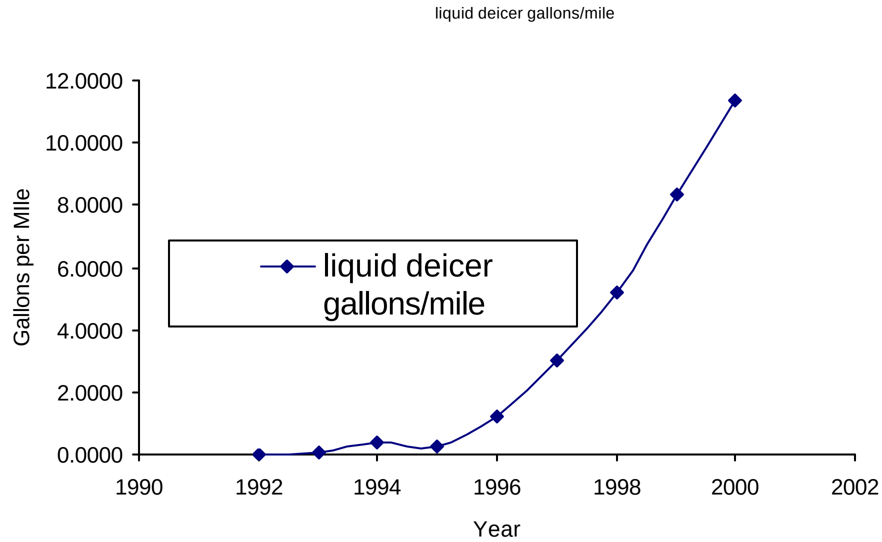


Figure 9.4.4 CDOT Trend of the Use of Liquid Deicer

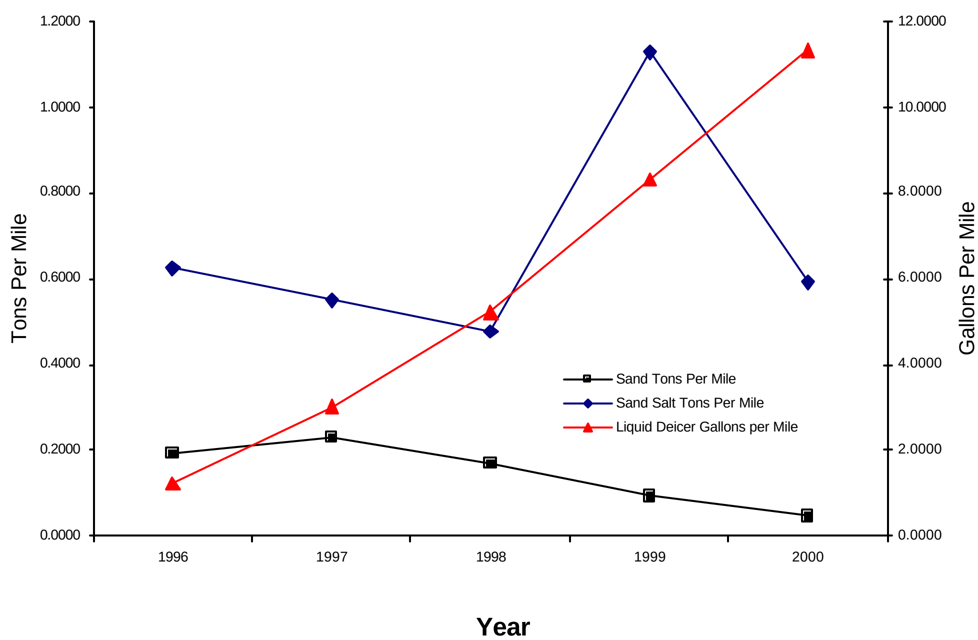


Figure 9.4.5 Materials Usage per Mile

Figure 9.3.4 shows that the total windshield damage cost began to decrease in 1998 while the Colorado population was still rising. This cost reduction could very well be related to the increasing use of deicing chemicals and decreasing use of sand and rock salt as roadway traction enhancement agents. In fact, this reduction in the use of solids might have also contributed to the reduction of PM-10 in the Denver air and air elsewhere in the state. In short the CDOT shift in winter roadway maintenance policy has contributed to a reduction in vehicle glass damage, and might very well have contributed to the cleaner air in Colorado.

Figure 9.4.1 shows that the total windshield damage claims count increased only slightly while the policy count has drastically increased due to the population boom. In other words, the claim/policy count rate has decreased. The CDOT policy shift of using less sand and more liquid deicers has contributed, at least partially, to this decreasing trend of the claim/count ratio. It is clear that the CDOT new policy of replacing sand with liquid deicers reduces the windshield damage claims and, thereby, the amount of damage caused by rock particles striking windshields. While it would seem rational for the traveling public to request complete phase out of sand use and adoption of liquid deicers, some sand use is still necessary during inclement winter weather conditions. This is to avoid traffic accidents and maintain highway safety. Thus, it is necessary for CDOT and municipalities to formulate an ideal (or optimal) mix use of liquid deicers and sand to optimize highway safety and minimize the cost to the traveling public.

Quality control of sanding materials is essential to minimize the windshield damage. Evidence has shown that larger rocks cause more severe damage to windshields and the particles with size from ¼ to 3/8 inches seem to be most ideal for use on highways, because they cause minimal damage to windshields. Field experiments have also shown that the damage caused by angular grains is not as severe as the rounded grains. Thus, the crushed rocks of the above-said grain size seem also appropriate as sanding material.

9.5 Summary and Conclusions

In the past decade, Colorado has experienced one of the nation's highest population growth rates. This resulted in the rapidly increasing number of automobiles on the highway and naturally the rise in the insurance policy count and total insurance cost. To enhance highway safety, maintain high air quality and reduce the cost to the traveling public, CDOT and municipalities have engaged in an effort to optimize the use of sand on Colorado highways and streets. Rapidly, liquid deicers have replaced a great portion of sand as recommended in the finding in the CDOT-funded research project on "Environmentally Friendly Sanding and Deicing Practices" performed at the University of Colorado at Denver. In the last six years, the Colorado air quality has not violated the EPA PM-10 air quality standard. The above shift in the winter roadway maintenance policy has benefited, at least partially, the Colorado air quality. The effects of the policy shift of CDOT and municipalities winter roadway maintenance on the roadway maintenance budget and the cost of windshield damage are analyzed in this chapter and the findings summarized as follows:

Because of inflation, the total cost for windshield repair and replacement will continue to rise despite the decrease in the claim/policy count ratio. To reduce the CDOT maintenance budget, the windshield damage cost to the traveling public and, at the same time, to maintain highway safety, CDOT, Colorado municipalities, and the auto insurance industry need to continue to be engaged in the formulation of an optimal winter roadway maintenance strategy that optimizes the use of sand and liquid deicing chemicals, maximizes winter roadway safety, and minimizes the winter roadway maintenance budget and the cost to the traveling public in terms of windshield damage.

The optimal winter roadway maintenance strategy (OWRMS) involves timely application of traction enhancement materials, snow and ice removal, and the optimum mix use of liquid deicers and sand. To reduce damage, it is recommended to use angular to subangular sand grains with particle size ranging from 0.25 to 3/8 inches.

Because of the cost differential, whenever safety permits, it is recommended that the insurance industry grant more repair and less replacement of damaged windshields.

The driving public can also help minimize the cost by not engaging in speeding, weaving and driving too close to the Jersey barriers and on the shoulder, where rocks usually rest. The installation of mudguards can also help reduce the insurance cost to the traveling public. The mudguards intercept the flying rocks or reduce their velocity and thereby minimize the chance and cost of damage. With the collaborative effort of CDOT, municipalities, insurance companies, and the public, the Colorado roadways can become safer and less costly to maintain and the traveling public can experience a reduction in cost associated with windshield damage.

10. Overall Summary and Conclusions

10.1 Summary

In the past decade, Colorado has experienced one of the nation's highest population growth rates. It has accelerated in the last six years. This growth has led to the rapidly increasing volume of automobiles on Colorado highways and naturally the rise in the insurance policy count and total cost. To enhance the highway safety, maintain high air quality and reduce the cost to the traveling public, CDOT and municipalities have engaged in an effort to reduce the use of sand on Colorado highways and streets. Rapidly, liquid deicers replace a great portion of sand as recommended in the finding in CDOT funded research project on "Environmentally Sensitive Sanding and Deicing Practices" performed at the University of Colorado at Denver. This policy shift has contributed to the Colorado high air quality. Colorado has not violated the EPA PM-10 air quality standard in the past six years. Another benefit of this policy shift is the reduction of windshield damage and associated insurance claims, as demonstrated in the decrease in the claim/policy count ratio from 1996 to 2000. Its effects on the CDOT's winter roadway maintenance budget and the cost of windshield damage are analyzed in this chapter and the findings summarized in the following:

- The windshield damage cost analysis shows that the total cost for windshield repair and replacement continues to rise despite the decrease in the claim/policy count ratio. This imposes the financial burden to the traveling public. Thus, it is in the best interest of both CDOT and the traveling public to devise an optimal winter roadway maintenance strategy that minimizes the winter roadway maintenance budget and the windshield cost to the traveling public.
- This optimal maintenance strategy involves an optimum mix use of liquid deicers and sand without the total elimination of the latter. CDOT and all municipalities will have to control the size and shape of rocks. Rock particles with size ranging from ¼ to 3/8 inches with subangular and angular particle shape are a good choice.

- Because of the cost differential, to reduce the windshield damage cost, it is recommended that the insurance industry begin to grant, whenever situations warrant, more repair and less replacement of damaged windshields.
- The driving public can also help minimize the cost by not speeding, weaving and driving too close to the Jersey barriers and shoulders where rocks usually rest. The installation of mudguards can also help because of the blockage of flying rocks and reduction of rock velocity.
- With the collaborative effort of CDOT, municipalities, insurance companies, and the public, the Colorado roadways can be safer and less costly to maintain. In addition, the traveling public can experience a reduction in vehicle repair costs associated with winter highway driving.
- The regional cost of winter roadway maintenance varies with the difference in maintenance practices due to geographic conditions, weather patterns, needs and available resources. The Eisenhower Tunnel region, with more miles of steep-grade highways and severe weather conditions, usually relies on sand for instant traction enhancement. This wide variation in weather patterns and road grades causes vastly different winter roadway maintenance practices and maintenance costs.
- From the materials standpoint the trend is clear: the state is moving towards using more liquid deicers even at a higher application cost by about 20 cents per mile. This high cost is mainly caused by the early application of liquid deicers as anti-icing agents.
- Colorado has two major interstates, I-70 and I-25. The rest of the state is served by many two to four-lane highways. The maintenance practices between the interstates and other state highways are quite different. This causes the vastly different winter roadway maintenance costs among regions. The regional data are compiled into the statewide data for the purpose of discerning the annual cost variation.
- The statewide trend is investigated in the following areas: annual snowfall, use of sand and liquid deicers, personnel cost and equipment cost. It is interesting to note that the annual snowfall is about 50 to 60 inches with the exception of a severe

snowstorm like the one in 1997 dropping 21.9 inches in Denver. As for the traction enhancement materials used, the state has experienced a significant downward trend in the use of solids such as sand and rock salt, while the use of liquid deicers has increased many-fold since 1994. Personnel and equipment costs, however, have remained relatively steady over the study period with the exception of special conditions.

- The policy shift is most pronounced in the Denver region. From 1994 to 2000, the use of deicers (liquid and solid) has increased from 0% to 60%, meanwhile the use of sand has decreased from 100% to 40%. The main driving force behind this drastic shift is the improvement and maintenance of air quality. The Denver area has not exceeded the EPA PM-10 standard in the last six years since the implementation of the policy shift.
- Because of the policy shift toward the use of deicers, the sand cleaning effort has decreased drastically. Besides, the use of deicers as an anti-icing agent also has made it easier for snow removal. When all is accounted for, the use of deicers is more cost-effective than the use of sand/salt mixtures on a per mile basis.
- The winter roadway maintenance practice is still quite region dependent. This is mainly because of their differences in geographic location, population size, roadway types, weather patterns and materials availability. While all regions use some chemicals, the majority of remote regions still rely predominately on sand/ salt mix. The areas with the major thoroughfares such as I-70 and I-25 rely much more heavily on deicers.
- The practice of winter roadway maintenance has a very large effect on the cost of car windshield damage. Ideally to eliminate the cost of the windshield damage requires elimination of the use of sand. The complete elimination of sand is not advised because of the safety concerns during unexpected inclement weather conditions.
- Rock particles of angular shape have shown to cause less severe damage with “star” shape facture, while round particles cause more severe and larger “bulls-eye" fractures. Less dense lava rocks cause a scattered pattern of surface chips upon impact with windshields.

10.2 Conclusions

Critical concluding remarks are outlined as follows:

- Since 1993, CDOT has shifted its winter roadway maintenance strategy to de-emphasizing the use of sand and rock salt and increasing the use of liquid deicing chemicals. This policy shift is, however region-dependent. It depends strongly on its geographic location, the needs of the regional population, availability of materials and financial resources, and regional environmental requirements.
- This policy shift involves an optimal maintenance policy with the optimal mix of sand and liquid deicers. Besides the timing of the snow removal, application of traction enhancement agents and sand sweeping after snow melt are critical to a successful winter roadway maintenance practice.
- Major benefits of increasing use of liquid chemical deicers include the reduction of the insurance cost because of reduced chance of windshield damage and cleaner air. Since the implementation of the findings from the research on "Environmentally Sensitive Sanding and Deicing Practices," in 1994, the Denver metropolitan region has not violated the EPA PM-10 Standard.
- Colorado sanding materials vary from bottom ash (or lava rock) to fine gravels with the grain size mostly smaller than 3/8 inches and less than eight percent of fines. The gradation ranges from uniform to well-graded and the grain shape ranges from angular to rounded.
- Particles of rounded shape and larger momentum (mv) usually cause more severe damage than the angular ones of the same mv, where m is particle mass and v is the particle velocity.
- At a cruising velocity, the rebounding of the sand particle-pavement system after pressure removal causes the sand particle to become airborne nearly vertically to a height of a few feet with an initially velocity of around 10 to 15 ft/sec.
- Sanding debris is responsible for windshield damage. But sand grains smaller than 3/8 inches are usually not responsible for severe damage at a velocity slower than 40 miles/hour.

- Although minimizing sanding will reduce the windshield damage cost, the issue of its effect on safety must be examined.
- The increasing use of deicing chemicals has resulted in the decrease in the insurance cost to the driving public and air pollution even in the population boom of the last decade.

10.3 Recommendation for Further Study

The following areas are recommended as potential areas for future research:

- The long-term effect of the policy shift toward heavy use of deicers on air and stream water quality, pavement integrity, and subgrade properties.
- The manner in which the following factors affect the rock airborne mechanism: engineering properties of pavement, subgrade, rock particles and tires, driving velocity and acceleration, and the roadway surface conditions.
- The effect of the roadway maintenance policy shift on the traffic accidents and vehicle damage other than windshields.
- Pavement surface traction after the application of deicers and snow melt.

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2. Nien-Yin Chang, et al, “Environmentally Sensitive Sanding and Deicing Practices,” Final Research Report, sponsored by CDOT and FHWA, 195 pages, 1994.
3. NCHRP Synthesis 207, “Managing Roadway Snow and Ice Control Operations.” TRB, NRC, 1994.
4. Transportation Research Record No. 1741, “Advances and Issues in Snow-Removal and Ice-control Technology.” TRB, NRC, 2001.
5. William M. Lewis, Jr., Western Environmental Analysts, “Studies of Environmental Effects of Magnesium Chloride Deicer in Colorado,” CDOT Final Report No. CDOT-DTD-R-99-10, Sponsored by CDOT and FHWA.
6. Candis Claiborn, et al, “Measurement and Source Apportionment of PM10 Roadway Emissions,” WA-RD 303.1, Final Report, sponsored by WA DOT and FHWA, 1994.
7. Chatten Cowherd, “Particulate Matter from Roadways,” CDOT Report No. CDOT-DTD-98-8, sponsored by CDOT and FHWA, 1998.

Appendix A

Field test for windshield damage


Figure 1 Test Site


Figure 2 Slingshot set-up


Figure 3 Test vehicle


Figure 4 High-speed camera


Figure 5 Damage pattern

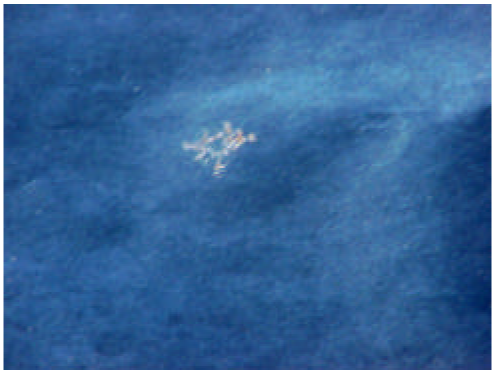


Figure 6 Damage pattern

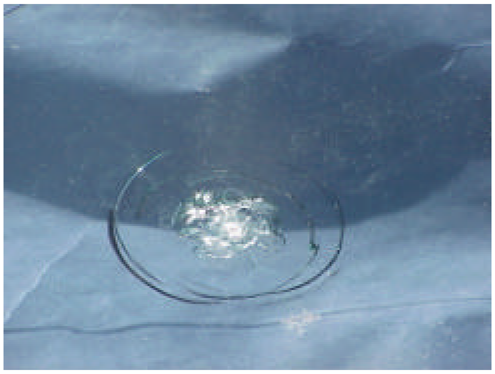


Figure 7 Bulls-eye pattern damage

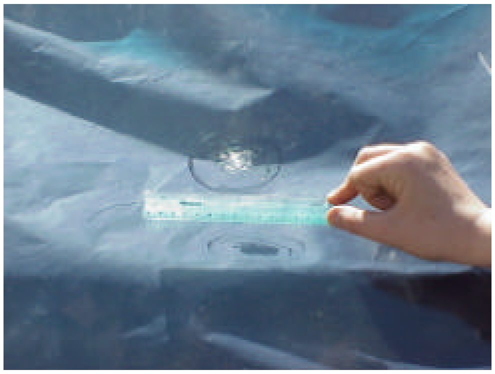


Figure 8 Bulls-eye pattern damage

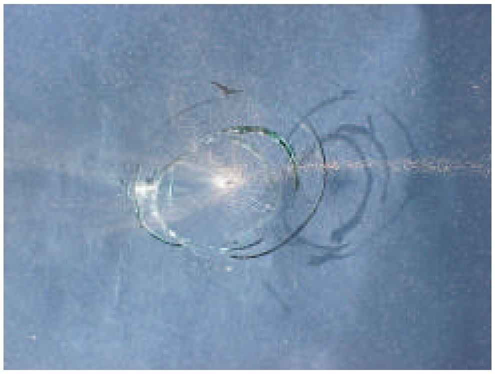


Figure 9 Bulls-eye pattern damage

Figure 10 Bulls-eye pattern damage

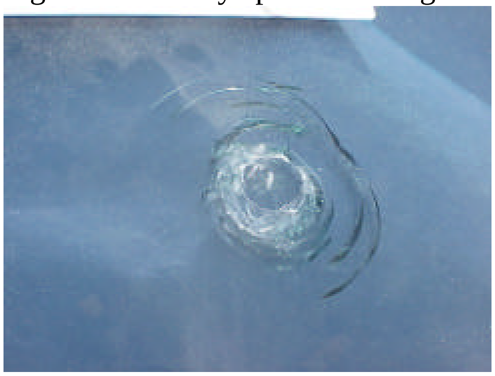


Figure 11 Bulls-eye pattern damage

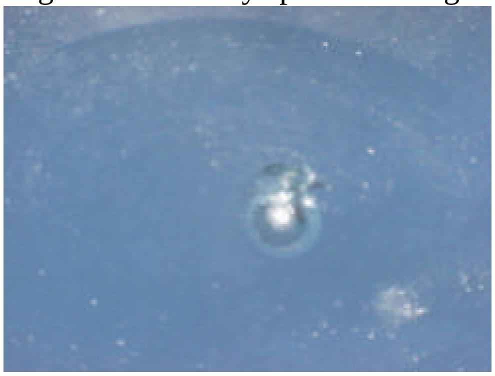


Figure 12 Chip fracture

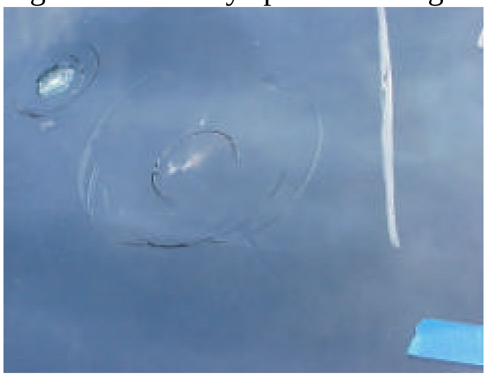


Figure 13 Bulls-eye pattern damage

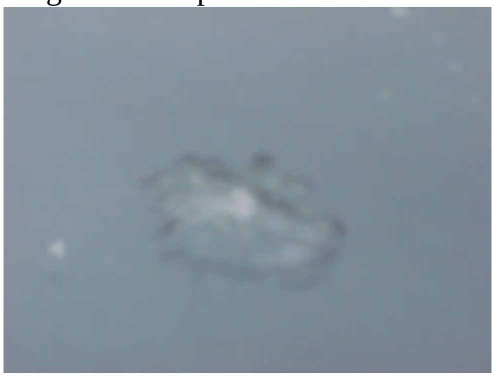


Figure 14 Chip fracture

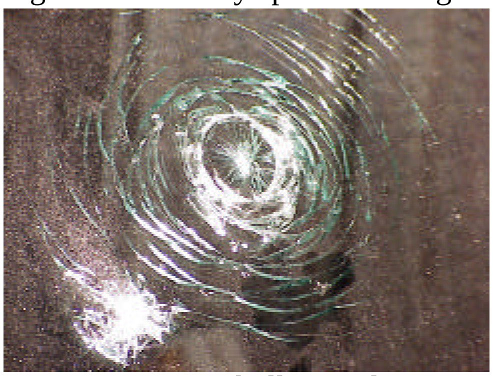


Figure 15 Severe bulls-eye damage pattern

Appendix B

Field test for assessing the effect of grain characteristics on windshield damage

Fig 1 Test B sample particles

Fig 2 Small Round, .17g, ρ=2.47

Fig 3 Med. Round, .22g, ρ=2.47

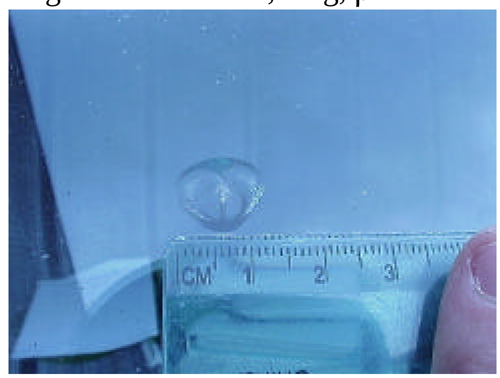


Fig 4 Lrg. Round, .41g, ρ=2.47

Fig 5 Lrg. Sub-Ang, .50g , ρ=2.73

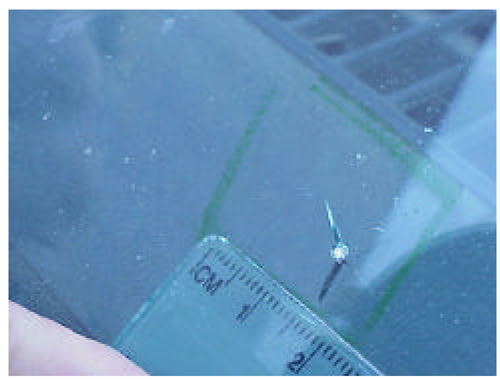


Fig 6 Small Sub-Rnd, .09g , ρ=2.46

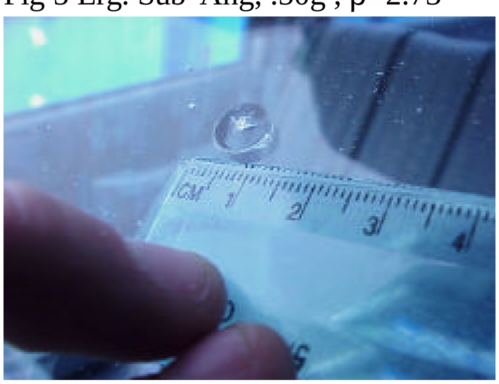


Fig 7 Med. Sub-Ang, .13g , ρ=2.46

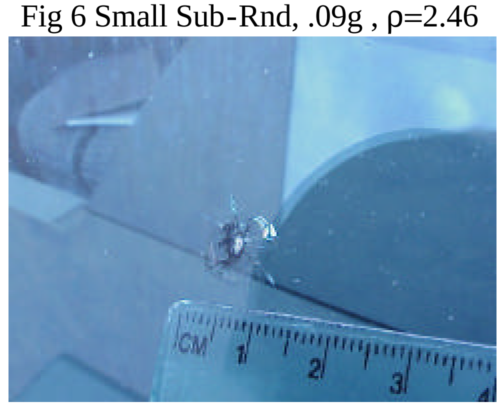


Fig 8 Small Sub-Ang, .14g , ρ=2.57

Fig 9 Fractures

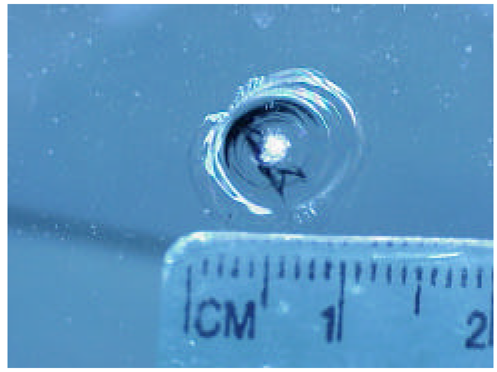


Fig 10 Conchoidal fracture

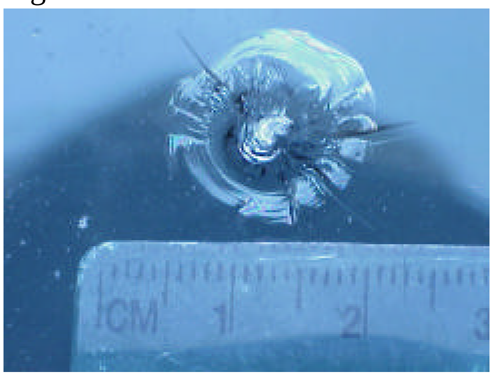


Fig 11 Star fracture

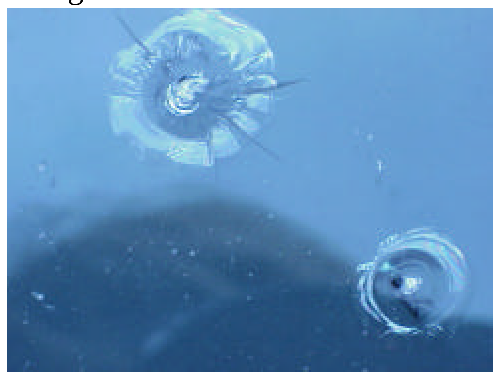


Fig 12 Star fracture

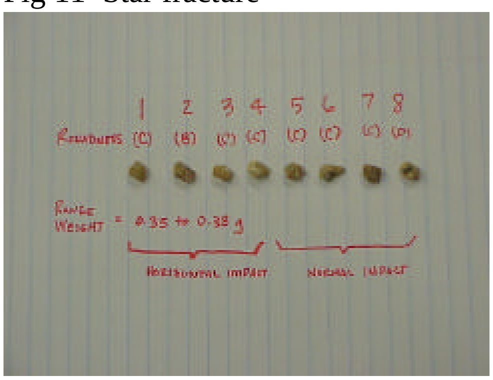


Fig 13 Varying velocity test grains

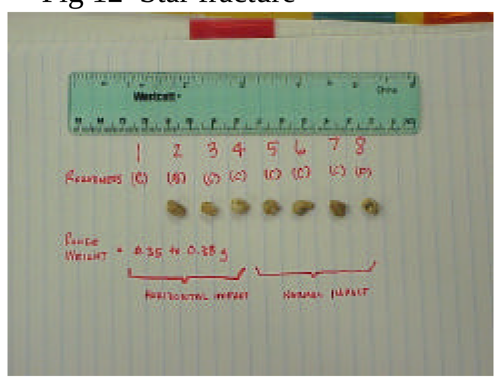


Fig 14 Varying velocity test grains

Fig 15 Hole #3, Sub-Rnd, ~0.36g

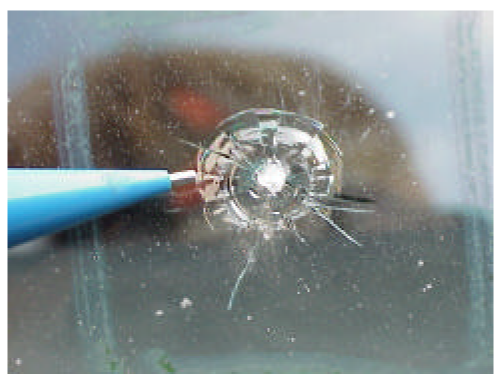


Fig 16 Hole #7, Sub-Rnd, ~0.36g

Fig 17 Hole #3, Rounded

Fig 18 Hole #9, Sub-Rnd, ~0.36g

Fig 19 Road test vehicle

Appendix C

Road tests


Fig 1 Road test


Fig 2 Road test- mounted camera

Fig 3 Coarse road test gravel

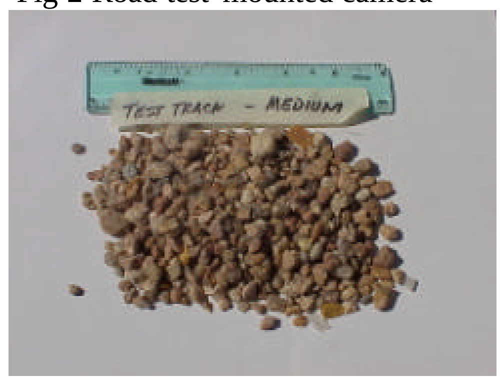


Fig 4 Medium road test gravel

Fig 5 Region 1 road test gravel

Fig 6 High-speed photo-1.111 sec

Fig 7 High-speed photo - 1.913 s

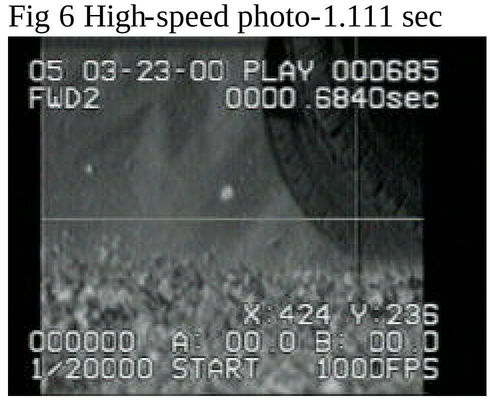


Fig 8 High-speed photo

Fig 9 Crack propagation

Fig 10 Conchoidal fracture

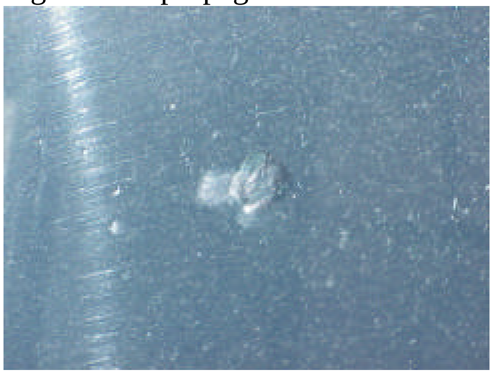


Fig 11 Surface chip

Fig 12 Random cracking

Fig 13 Crack propagation

Fig 14 Crack propagation

Fig 15 Surface chips

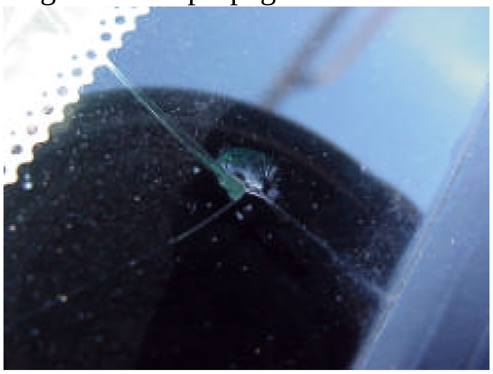


Fig 16 Crack propagation

Fig 17 Locating the fracture

Fig 18 Locating the fractures

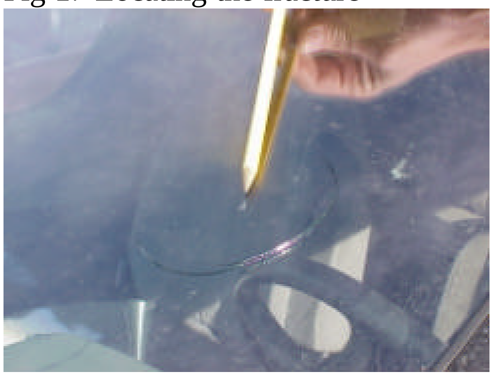


Figure 19 Bulls-eye fracture pattern

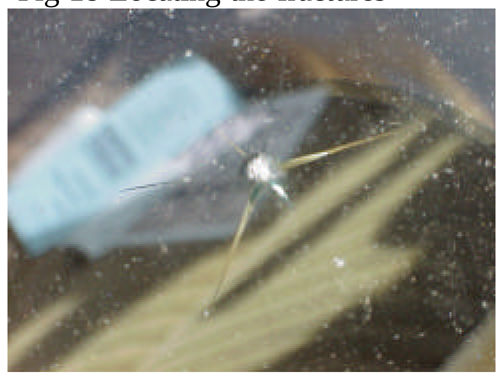


Fig 20 Star fracture pattern

Fig 21 Research team

Appendix D

Tire-rod interaction

Figure 1 Series 1

Figure 2 Series 1

Fig 3 Series 2

Fig 4 Series 2

Fig 5 Series 2

Fig 6 Series 3

Fig 7 Series 3

Fig 8 Series 3

Appendix E

Windshield damage survey

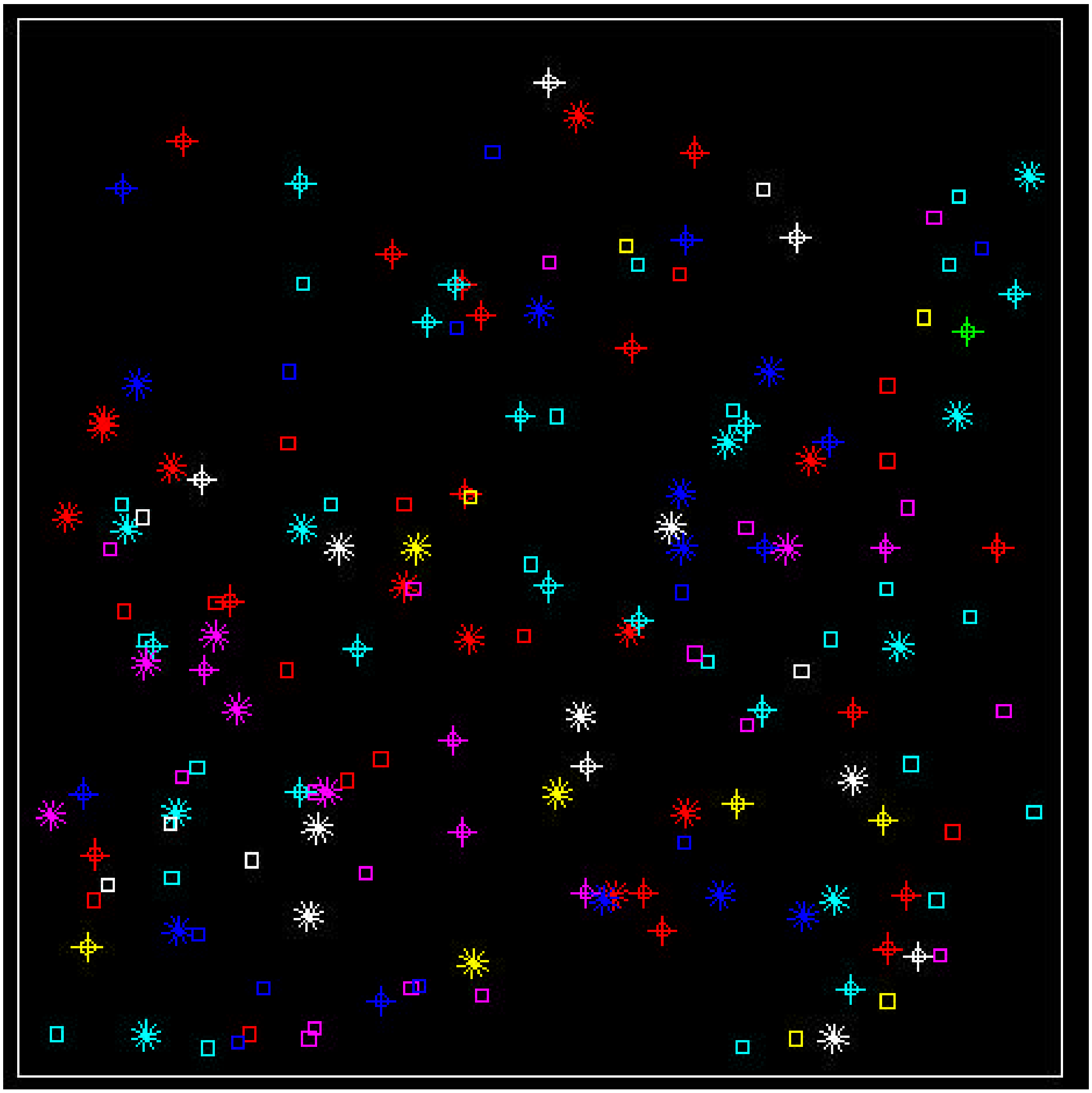


Figure 1 High Profile Vehicles

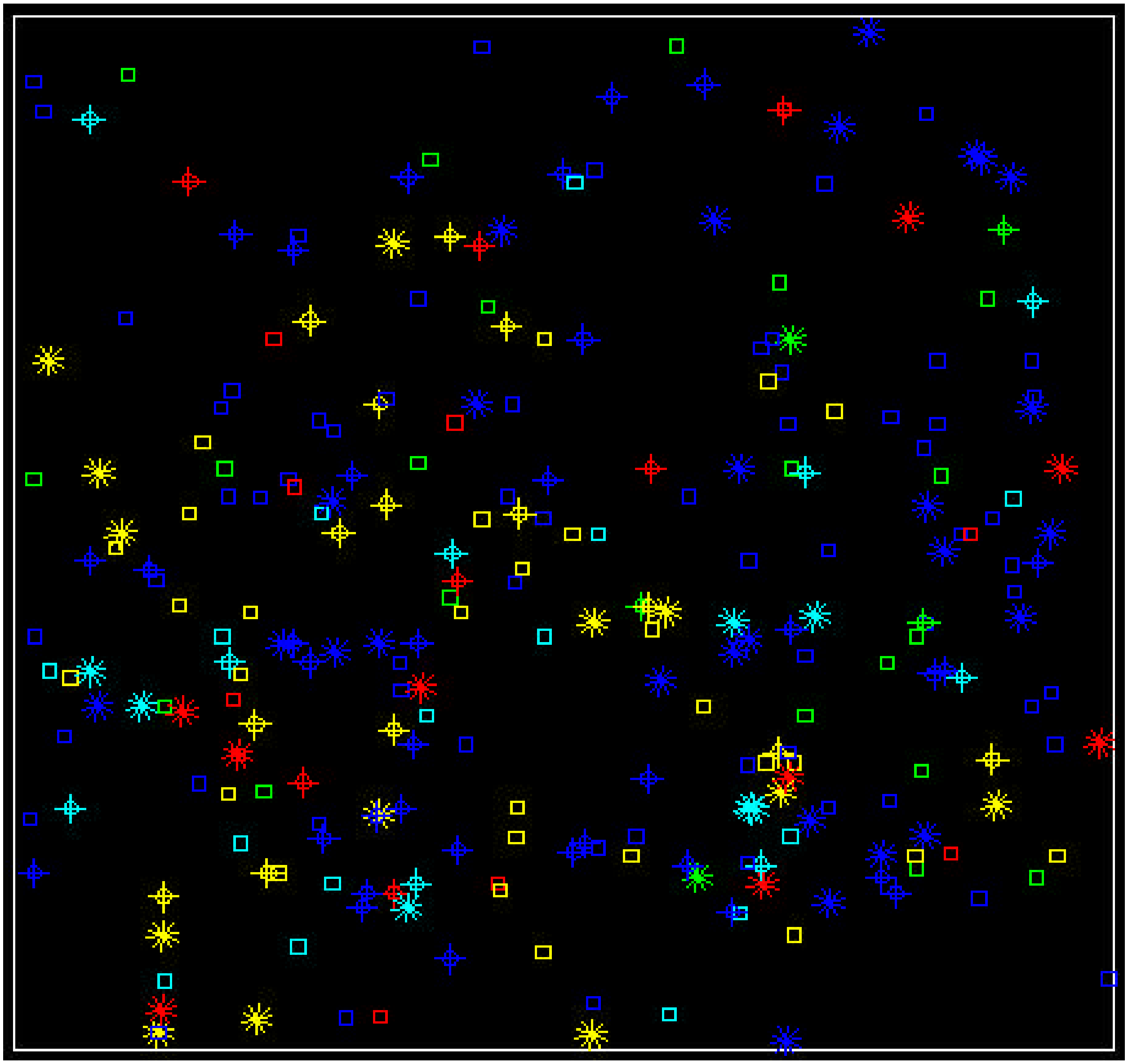


Figure 2 Low Profile Vehicles

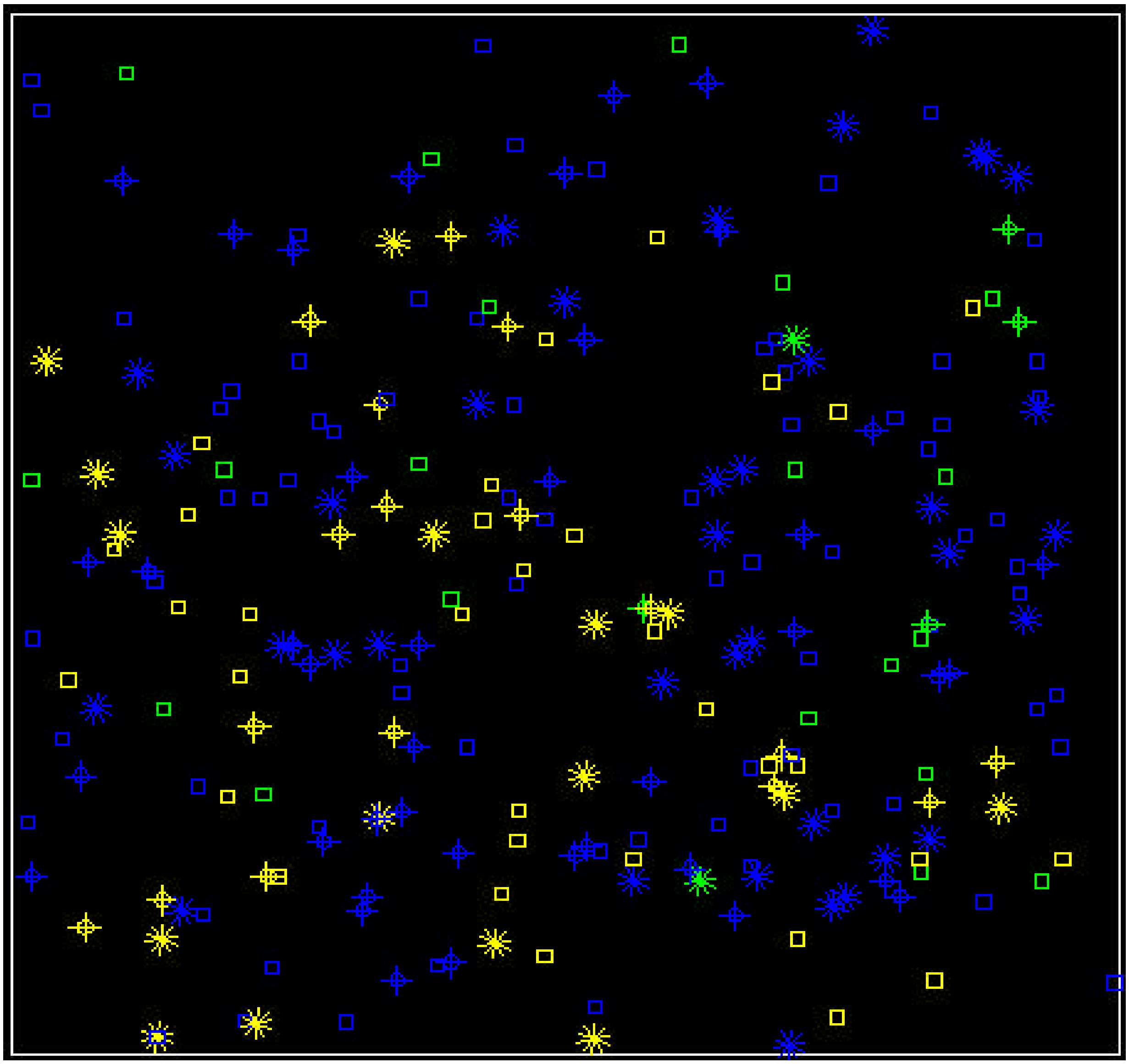


Figure 3 Vehicles with windshield angle under 35^o

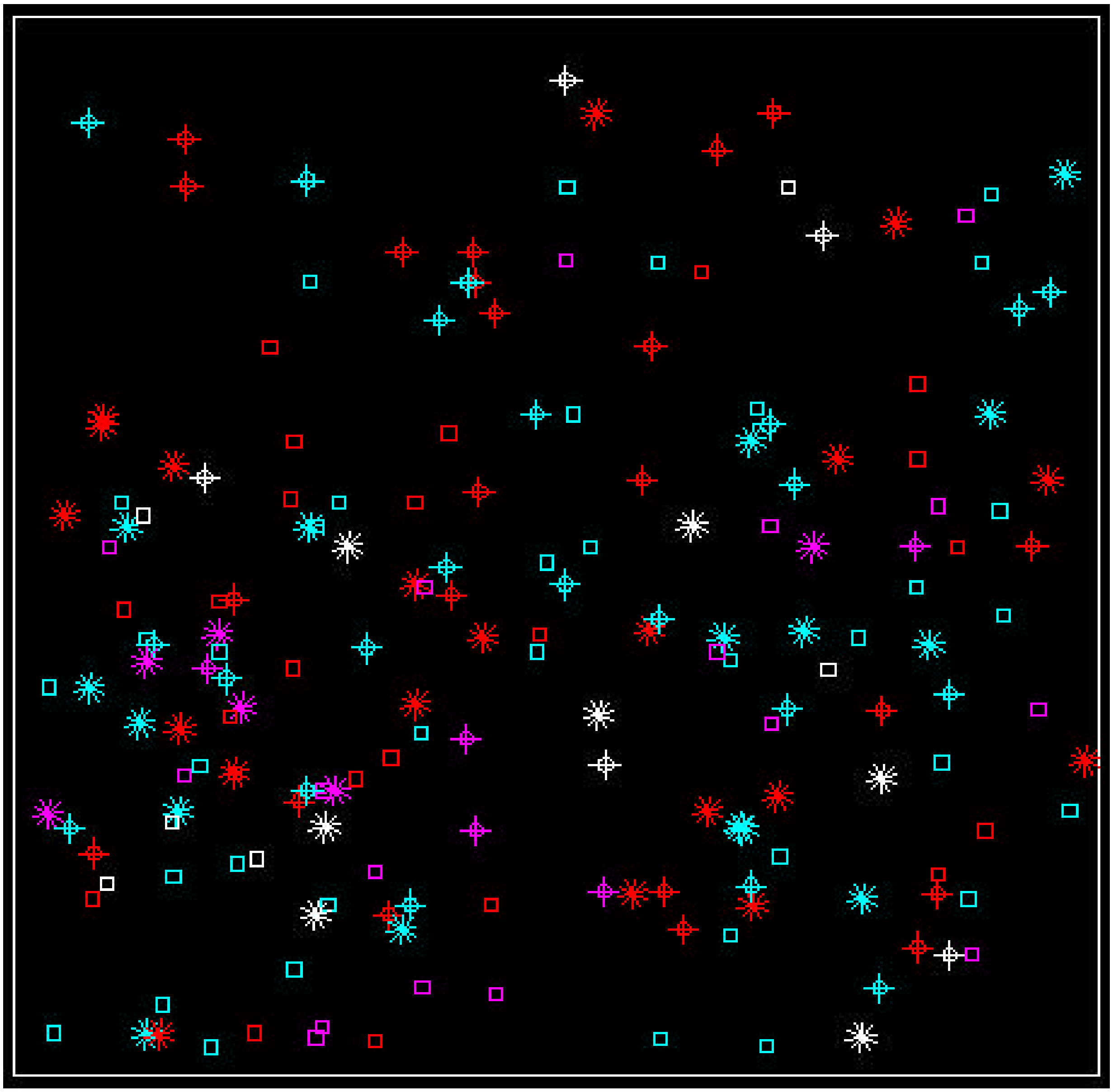


Figure 4 Vehicles with windshield angle over 35°

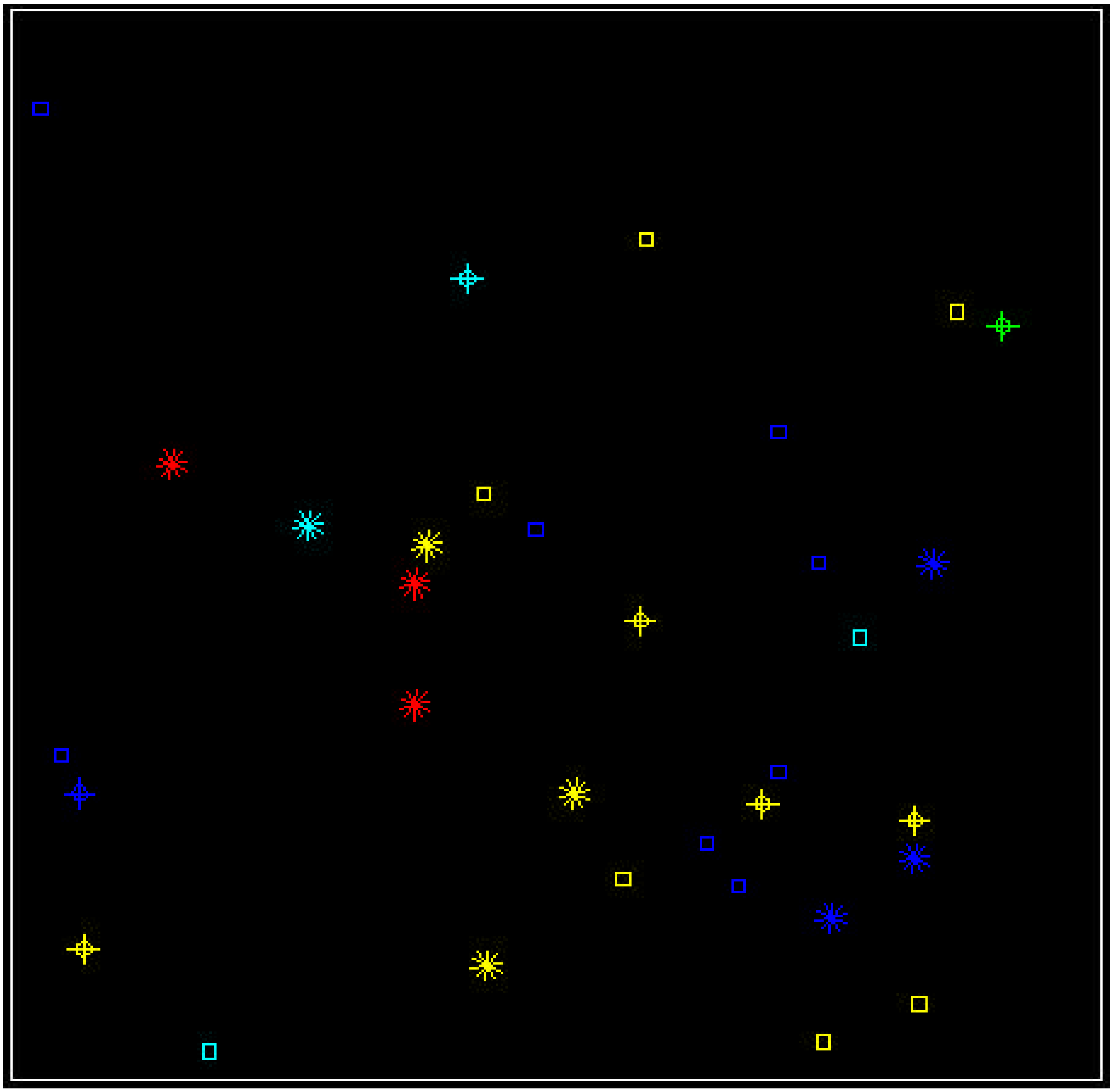


Figure 5 Vehicles with bottom distance under 40 inches

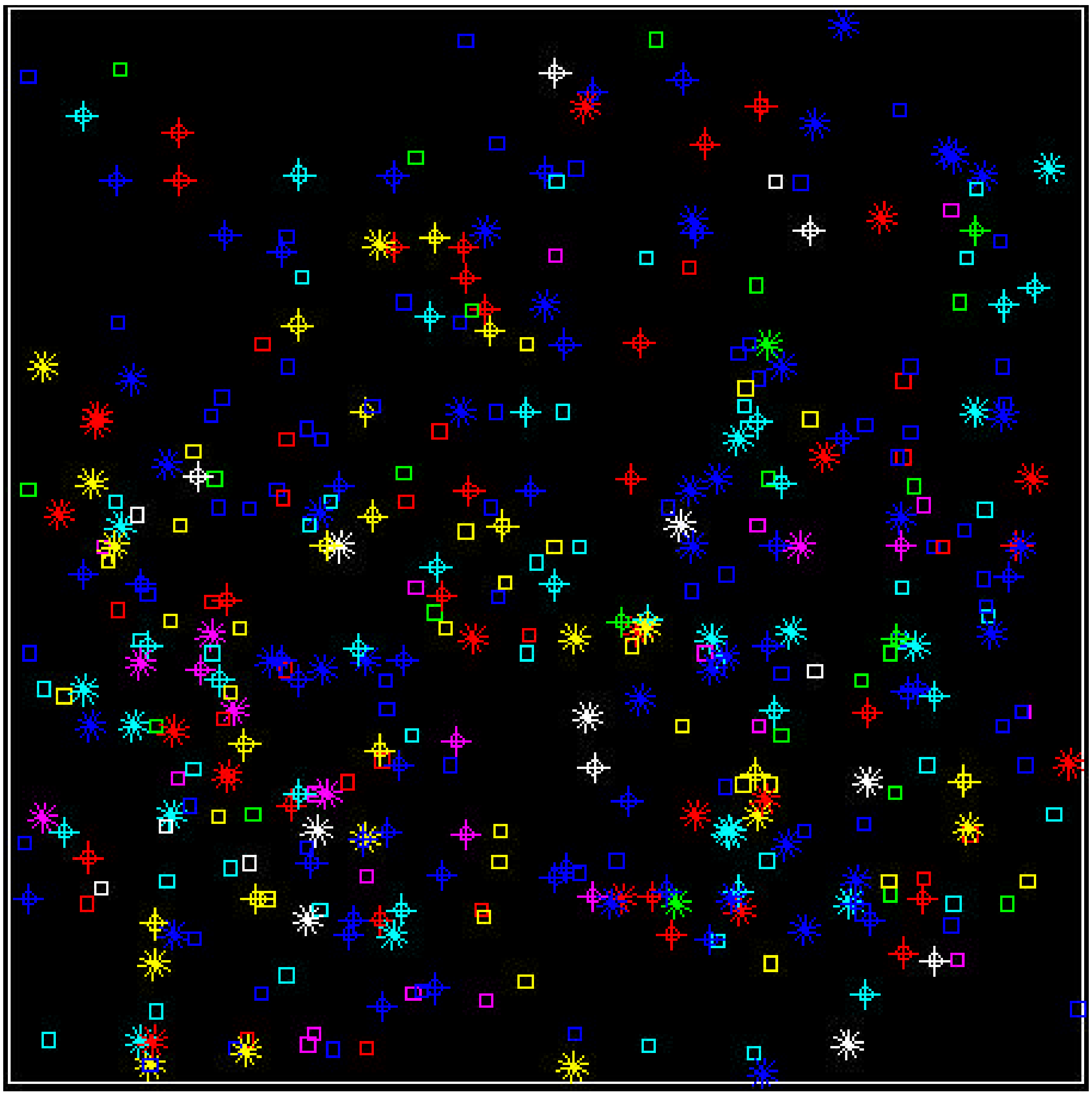


Figure 6 Vehicles with bottom distance over 40 inches

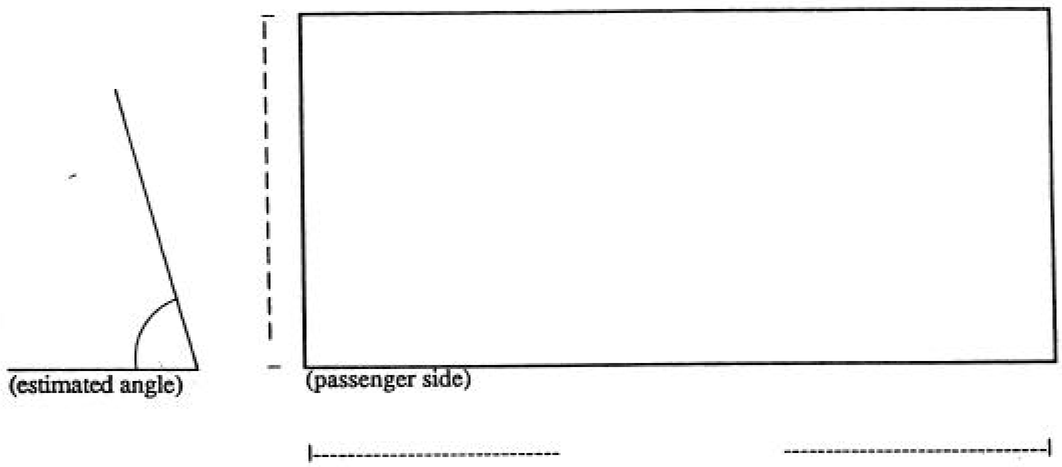
Windshield Damage Survey

Date: ____________________

License Plate: (state) ____________________ (#) ____________________

Profile: HIGH LOW

Type of Vehicle: ____________________



Top Height: ____________________ Bottom Height: ____________________

Top Distance: ____________________
(back from front of car)

Bottom Distance: ____________________
(back from front of car)

Height of front of car: ____________________
(not the front bumper)

General Condition of Vehicle: New Good OK Bad

Surveyors Initials: ____________________ ____________________

Figure 7 Windshield Damage Survey form

Table E.1 Windshield Survey Statistics

High Profile Bottom Height:

Column1	
Mean	46.26897
Standard Error	0.336729
Median	46
Mode	45
Standard Deviation	4.054756
Sample Variance	16.44104
Kurtosis	8.103871
Skewness	-1.13704
Range	35
Minimum	22
Maximum	57
Sum	6709
Count	145
Largest(1)	57
Smallest(1)	22

Low Profile Bottom Height:

Column1	
Mean	35.70336
Standard Error	0.1209
Median	36
Mode	36
Standard Deviation	1.979215
Sample Variance	3.917292
Kurtosis	9.700002
Skewness	1.798167
Range	15
Minimum	31
Maximum	46
Sum	9568.5
Count	268
Largest(1)	46
Smallest(1)	31

High Profile Top Height

Column1	
Mean	64.11806
Standard Error	0.322334
Median	64
Mode	64
Standard Deviation	3.868009
Sample Variance	14.96149
Kurtosis	1.482905
Skewness	0.148797
Range	22
Minimum	53
Maximum	75
Sum	9233
Count	144
Largest(1)	75
Smallest(1)	53

Low Profile Top Height

Column1	
Mean	51.33955
Standard Error	0.14265
Median	51
Mode	50
Standard Deviation	2.335286
Sample Variance	5.453561
Kurtosis	6.006421
Skewness	1.204133
Range	20
Minimum	43
Maximum	63
Sum	13759
Count	268
Largest(1)	63
Smallest(1)	43