EPA-600/2-76-105
May 1976

Environmental Protection Technology Series

AN ECONOMIC ANALYSIS OF THE ENVIRONMENTAL IMPACT OF HIGHWAY DEICING

Municipal Environmental Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

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by

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Contract No. 68-03-0442
OMB Clearance No. 158S 74012

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problems, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

The study contained herein involves an extensive examination of the costs incurred by society as a result of the use of highway deicing chemicals. The costs, which are examined separately for damage to each sector of the natural environment and to manmade goods, are shown to be substantial.

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ABSTRACT

This study involves an analysis of the cost of damages that result from the use of salt (sodium chloride and calcium chloride) on highways to melt snow and ice. A large literature search and several surveys were carried out to determine the types and extent of damages that have occurred. The report contains a Bibliography with over 320 references.

An in-depth analysis was performed on all of the data obtained. The major cost sectors examined were: water supplies and health, vegetation, highway structures, vehicles, and utilities. For each of the sectors, a cost estimate was developed. The total annual national cost of salt related damage approaches $3 billion dollars or about 15 times the annual national cost for salt purchase and application. While the largest direct costs result from damage to vehicles, the most serious damage in the long run seems to be the pollution of water supplies and the degradation of health which may result. It is particularly difficult to assign costs in this latter area and therefore the estimate may substantially understate the actual indirect costs to society.

These findings indicate that the level of salt use should be reduced. The amount of the reduction should be determined on the basis of local conditions.

This report was submitted in fulfillment of Contract No. 68-03-0442 by Abt Associates Inc., under the sponsorship of the Environmental Protection Agency.

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ACKNOWLEDGEMENTS

The contents of the report are a product of many contributors across the nation, and from several foreign countries. The project staff have been impressed by, and greatly appreciative of, the concern on the part of hundreds of individuals and agencies which have provided valuable information. Sincere thanks goes to all those who have helped make this possible.

Special thanks go to Adrian Clary of the Highway Research Board and Richard Hay of the Federal Highway Administration for their comments on a first draft of the highway and bridge damage section. Thanks also go to Robert C. Terry, Jr. of Arthur D. Little and The Salt Institute for their advice and assistance. The City of New York provided some very important reports on the damage to the West Side Highway.

This report was written by Donald M. Murray and Ulrich F. W. Ernst. Research Assistance was provided by Judy Poole, Ramon Estrada and Janice Darling. Advice given by Malcolm FitzPatrick was appreciated. Thanks go to Robert C. Anderson for his contributions, especially in the area of bridge and automobile damage, and to Gary J. Stensland for his work on the atmospheric content of salt. Mary Hobson displayed great patience in typing many drafts during the production of this report and her efforts are also appreciated.

The support of this effort by the Wastewater Research Division (Edison, New Jersey) of the USEPA Municipal Environmental Research Laboratory, Cincinnati, Ohio, and especially Mr. Hugh E. Masters, Project Officer, for his guidance, suggestions and inputs, and thorough manuscript review is acknowledged with gratitude.

SECTION 1

FINDINGS AND CONCLUSIONS

1.1 SUMMARY OF FINDINGS

There have been a substantial number of reports of salt related damage in the literature. Most of the reports are deficient in hard cost data. Consequently, by examining different small subsets of the data, various individuals have arrived at opposite conclusions: in some cases that salt damage is insignificant and in other cases, that road salting must be discontinued completely. Examination of all of the literature and contact with hundreds of persons and agencies who are aware of salt related damage has led to the finding that, in general, the damages are very large although not uniform across all localities. Through analysis of all of the available data, the best estimate (in many cases the lower bound) of the annual cost to the snowbelt states that results from the use of road salt is as follows:

	Total (in millions)
Water Supplies and Health	$ 150
Vegetation	50
Highway Structures	500
Vehicles	2,000
Utilities	10
Salt Purchase and Application	200
Total	$ 2.91 Billion

Furthermore, heavy salt use in many instances upsets the natural ecological balance resulting in damages which cannot be assigned a dollar figure. This is one of the many reasons that the above dollar amounts must be considered as lower bounds. The most potentially serious of all these damages are the irreversible ones, such as the risk of increased hypertension that results from the heightened levels of sodium in water supplies. For example, groundwater supplies have been most severely affected. Over 90 communities in Massachusetts have one or more supplies with a sodium content greater than 20 mg/liter, the maximum allowed for persons on low sodium diets. Over 30 water supplies in Connecticut contain more than 20 mg/l sodium and the number is increasing. As much as 5% of the population consuming water contaminated by road salt may be adversely affected.

The use of salt for winter maintenance generally results in better traction on the highways, but because of a number of confounding factors, especially driver behavior, the link between salt and safety has not been proved. While several studies have reported that salt reduces accidents, the methods of data collection and analysis have been found to be mathematically unsound.

Finally, carefully designed reduced salting policies seem to have gained public acceptance as a result of public information programs. The most notable case is the State of Connecticut where state salt use was reduced by 33% because of rising sodium content in water supplies. There is every reason to believe that the residents of individual cities and towns or other states would accept a salt reduction if the salt related damages were made known to them.

1.2 CONCLUSIONS

In the past a number of claims have attempted to downgrade the seriousness of road salt related damage by placing emphasis on the comparisons of the effectiveness of salt and sand, or by concentrating on the lack of importance of vegetation in comparison to human lives (i.e., safety on the roads). Because these claims do not address the whole problem, they are superficial, misleading, and in a few cases, irresponsible. The facts are:

- Several states have experienced significant increases of salt in groundwater and surface drinking water supplies that have been directly linked to the use of deicing salts.

- In particular cases, the levels exceed Public Health Service safety standards set in 1962 and in most cases the levels exceed the standards set by leading researchers, heart specialists and the American Heart Association.

- The cost in terms of permanent health degradation is extremely difficult to measure, but is likely to be very high.

- The cost of actual damage to vehicles, highways and structures, utilities, and vegetation are immense. The annual damage costs at a very lower bound, approach $3 billion. This "hidden" cost is almost 15 times the annual national budget for the purchase and application of road salt, and about 6 times the entire annual national budget for snow and ice removal.

The implications of these facts are clear. Without a doubt the most serious problem is our water supplies. While the cost of damage to bridge decks and vehicles is high, but reversible, the damage to health may not be reversed. We can no longer afford to ignore the fact that we are depositing large quantities of salt into the water that nature provides us and upon which are dependent every moment of our lives. The most advanced medical research indicates that water with more than 20 mg/l sodium is unhealthy and detrimental to a substantial fraction of the population. The American Heart Association supports this fact. Disregard for the quality of drinking water in this and any instance is extreme negligence and we must face the issue squarely. Road salt may be only one of the many serious pollutants in our environment, but that is no excuse to allow the present situation to exist any longer. In order to avoid further damage and high costs, salt use for winter maintenance must be reduced in many areas.

SECTION 2

RECOMMENDATIONS

The level of salting should be reduced by an amount determined by local conditions such as the effect of salt laden runoff on water supplies, the level of public demand for bare pavement, and the size of the winter maintenance budget. Greater emphasis should be placed on non-chemical methods of snow and ice control (such as increased plowing and sanding.) Determination of the required level of bare pavement is a burden that should not be the sole responsibility of highway maintenance departments. The departments should seek advice from all interested groups and the public at large in order to achieve the best possible level of road maintenance within given environmental constraints. Through public affairs programs, the public should be made aware of the tradeoffs and alternatives involved. Changes to winter road policies should have public support and should be given a thorough public announcement before they are commenced.

There should be a greater emphasis on the training of drivers so that they will have the ability to drive under conditions of snow and ice, and less emphasis on the concept of guaranteed "June travel in January". Moreover, an operating policy to encourage motorists to stay off the roads during and immediately after storms would facilitate snow and ice removal. Restricted driving under short term emergency snow conditions should be considered.

The snow belt states should provide for testing of public and private water supplies, and should provide funds for replacement of public and private wells (as has been done in the State of New Hampshire). State legislation should be passed allowing individuals to have standing in court to sue for damages when water supplies show an abnormal and hazardous increase in sodium content. The law should place the burden of proof on the highway departments that the cause was not from road salt. Finally, the states should consider instituting a requirement that all salt users file an Environmental Assessment.

While these measures may seem burdensome, they are necessary in order to insure that we maintain our high quality of water and that large costs are not incurred as a result of winter highway policies.

SECTION 3

INTRODUCTION

3.1 THE USE OF SALT FOR DEICING

Extensive use of salt, both sodium chloride (NaCl) and calcium chloride ($CaCl_2$), for snow removal operations began during the early 1960s. Prior to that time highway maintenance departments depended primarily on abrasives such as sand and cinders, in combination with plowing, to clear snow and ice from highways. Salt was generally used as an additive to the abrasives to prevent freezing. However, from practical experience, maintenance departments began to appreciate the effect that salt had on accelerating the melting rate of ice and snow. Through experimentation, maintenance engineers learned that direct application of salt before, during and/or after a snowstorm greatly facilitated their snow removal operations, both in terms of time and in terms of budget. Since that discovery, the obvious has occurred. The use of salt for snow and ice removal has grown rapidly, in some cases by as much as 900% in the past 15 years (299). The extensive use of salt has been associated with a significant amount of damage. While there have been many reports on this damage, there has not been a comprehensive examination of the total impact of all salt related damage.

There is no question that salt is an excellent tool in snow removal operations. There also is no question that in terms of time and budget constraints for snow removal operations alone, the usage of large quantities of salt in conjunction with plowing is essential. Highway departments, operating under the goal of creating the safest driving conditions, believe that a policy of maximum bare pavement in a minimum time is optimized through extensive use of salt, given their budget constraints. In fact, some highway departments, in their eagerness to perform well and meet their goals, have often used salt in an inefficient manner. This has largely been eliminated now by education and understanding as a result of activities of the Salt Institute (312,313), the Environmental Protection Agency (304, 310), the Massachusetts Special Commission on Salt Contamination (4) and many others (see Bibliography: Maintenance Procedures and Regulations). The result has been a more effective use of salt with essentially no reduction in its level of usage (288, 298, 290). Total salt use for snow and ice removal in this country now stands at approximately 9 million tons each year. As the number of miles of highways increases, so also can we expect the amount of salt usage to increase if we continue with our present policy (and if no alternative method of snow and ice removal is found).

The concept of June travel in January, better known as the "bare pavement policy," has led the highway departments and the public to the situation in which we currently find ourselves. This situation has become increasingly complicated over the past 10 years, and especially during the past 4 to 5 years, because of the growing number of reports of damage to water supplies, vegetation, and the very vehicles and highways that originally served as the only focus of attention.

The concern over salt related damage has been increasing rapidly, probably exponentially, as the large (but only representative) bibliography at the end of this report demonstrates. The reports on instances of damage are extensive and well documented. There have been several excellent works done to summarize these reports (1,4,15, 16,26,38,42) and there have been many excellent in-depth studies on certain areas of damage (see Bibliography). Probably the best example of the latter is the work done for the Massachusetts Special Commission (4) and the follow-up by Robert Terry (53). Upon careful examination of all these studies and the other literature which has been reviewed, one can only come to the conclusion that the problem is potentially very serious. The situation has required a very careful assessment and the current guidelines under which snow removal procedures operate requires thoughtful consideration.

It is in this context that the idea for this project was formulated. Previous studies, as thorough as they were, did not assess the entire problem of damage in comprehensive terms including an economic analysis. Logically, no amount of damage claims, without the necessary economics, could enable a rational salting policy to be determined, except in the most extreme cases. Without such an economic analysis, no alternative to salt, whether it be more snow left on the highways or a more expensive replacement for salt, could ever be economically justified.

Consequently this analysis of damage from road salt was undertaken in order to assess the situation in the best possible manner. In all phases of the study there has been a constant effort to make the analysis quantitative. In some instances, because of the lack of cost data, this has simply been impossible. However in these cases every effort to perform an unbiased qualitative assessment has been made.

The authors have been impressed not only with the extensive reports of damage and the cost of that damage, but with the extensive amount of damage in one sector. Rusted vehicles and bridges, while costly can be replaced. Damaged vegetation can be ignored by those who do not incur the cost. But pollution of our water supplies is a serious matter. This is not to say that all road salt usage leads to water pollution, but it has in many instances. The medical implications of salt in drinking water is not a matter to be taken lightly. Because of many unknowns, the economic analysis of the damage to water supplies is not able to point out how potentially serious the problem may be. However each reader, knowledgeable of the facts on road salt damage in our environment, must make a decision for himself. Hopefully in this way a rational solution will be found, and serious damage to our environment will be prevented.

The fact that damage from salt has reached the magnitude that it has should come as no surprise to anyone who understands the way in which our current situation has evolved. Highway maintenance departments have as their primary goals the requirement for providing maximum safety and convenience on the highways. The departments have performed well, especially considering the complexities involved in snow and ice removal. While the current practices may be near optimal in terms of the department goals (and the highway budget constraints), in many locations the practices are far from optimal in terms of our whole environment, man-made and natural. This situation has occurred primarily because (1) those who determine present maintenance policies are largely unaffected by the adverse environmental conditions (that is, they do not incur the full cost of the damage), (2) legal liability in some instances may have forced highway departments to give undue weight to accident prevention and (3) there have been no outside forces to regulate the department's activities. The result is a prime example of a situation in which external diseconomies (social costs not borne by those making decisions as to the level of activity) lead to a failure of unregulated markets to achieve efficient outcomes. Determining the precise level or combinations of winter maintenance policies that maximizes social well being within certain constraints is the crux of the problem. Theoretically, at least, this is accomplished by assigning prices to the various social and environmental values and choosing that outcome which maximizes total net value. However, as the presentation and analysis in Sections 4 and 5 demonstrate, it is not possible to assign exact costs to all items because their value is subjective. It is especially difficult in cases where irreversibilities are involved, such as with permanent health damage and vegetation death.

It is interesting to note that the concept of "public pressure for bare pavement" may have evolved simply because the public was unaware of environmental damage and thought that more bare pavement resulted only in a small increase in the maintenance budget. This attitude seems to be rapidly changing as the public becomes more aware of the need for a sound environment.

An observation of public opinion has surfaced as a result of a large scale survey concerned with road related issues in Pittsburgh. (69) Question 33 in that survey asked, "Would you be willing to see cinders or sand used as an alternative to salt if less road deterioration would result?" A "yes" response was given by 73.3%, a "no" response by 24.6%, and no response by 1.8%. Question 46 asked, "If it were shown that salt caused serious damage to your car, would you be in favor of discontinuing the use of salt?". A "yes" response was given by 69.6%, a "no" response by

26.8%, and no response by 3.6%. Although the phrases "less road deterioation" and "serious damage" are not defined in terms of cost, and although the respondents may not have been fully aware of the impact that salt reduction may have on snow removal or highway budget, these figures still seem to indicate that the "public pressure" may not be as unanimous as is generally thought by the maintenance departments, especially considering that only one cost sector was mentioned in each of the two questions. This is particularly true when the public is informed of the tradeoffs in terms of environmental damage. As a result of road salting contamination of many water supplies, the state of Connecticut has developed a differential salting policy with a total reduction in salt use of one third. Through public information programs and the resulting public awareness, the policy change seems to have been favorably received. There is every reason to believe that a rational and holistic salting policy would be welcomed by every community.

Section 4 of this report presents the evidence on the link between road salt and damage, and demonstrates the extent of that damage. Section 5 contains a thorough economic analysis of the damage and a summary of the costs involved.

3.2 SUMMARY OF APPROACH

This study involved the collection of a great deal of material, both from the literature and through personal contacts. Subsequently this material was examined for its validity and thoroughness, forming the basis for analysis. Assessment of this material, in both quantitative and qualitative terms, was then undertaken.

3.2.1 Literature Review, Surveys, and Personal Contacts

During the course of the project a complete review of the literature on snow and ice removal, salt use, and salt damage was made and the most relevant documents, over 450 in number, were obtained (out of an estimated 700 or more). Each one of these documents was carefully screened for its validity and relevance and over 300 have been retained in a bibliography at the end of this report.

The second portion of the research involved the mailing of surveys and letters to universities, Public Works Departments, Public Health Departments, and water companies. There were over 100 respondents who indicated that they had incurred damage, knew of damage in their area, or provided us with documents or contacts relating to salt related damage. Follow up was done in many cases in order to clarify responses or obtain further information.

As a result of the literature and surveys, close to 200 personal contacts were made either by letter or phone. Almost all of these contacts provided up-to-date information on salt related damage; as in the case of the literature, and the surveys, "hard" data on costs of damage was minimal.

Finally, all of the material gathered from the search and surveys was reviewed and evaluated. This forms the basis for the presentation on salt related damage in Section 4.

3.2.2 Approach to Analysis

Since the study was essentially restricted to readily available data, either in published form or in the form of accessible records, the analysis of the economic costs of damages attributable to the use of deicing salts was constrained by the opportunities offered by the available data. In order to generate key points of reference, the cost analysis was based on a general model which expressed the expected (or average) annual cost in a particular damage category as the product of the expected magnitude of total damages (which in turn is the product of the probability of occurrence times the damage per occurrence) and the cost per "unit" of damage.

This general cost model provided the basis for examining the literature and other materials that had been accumulated in the study. Considerable efforts were undertaken to adapt the available information to fill the data needs of the study. However, in most cases, the estimation procedures used to quantify certain parameters of the cost function were too broad, given the nature of the available data. In these cases, costs were estimated on an ad hoc basis, e.g., by a weighted extrapolation of detailed cost data for a particular state or region.

The analysis comes closest to the ideal in the case of automobiles, in which the study could draw on previous work in the appropriate direction by one of the consultants to the study. The analysis of the costs of accelerated corrosion of automobiles used detailed data on depreciation rates in a significant sample of metropolitan areas, and estimated the net effects of deicing salts through multivariate analysis.

SECTION 4

SALT RELATED DAMAGE

As stated in Section 3.1, the purpose of this study has been to factually ascertain the types, extent, and monetary value of damage that has taken place in the total environment as a result of road salting. The purpose of this section of the report is to present a summary of the material which has been gathered from an extensive literature review and from personal contact with highway officials, public health officials, researchers, manufacturers, utility companies, and others. In the individual sections on damage, reference is made to major studies and in some instances to specific research, but space simply does not allow an examination of all of the documents listed in the Bibliography. The presentation is primarily centered around an explanation of how damage occurs, accompanied by actual case examples.

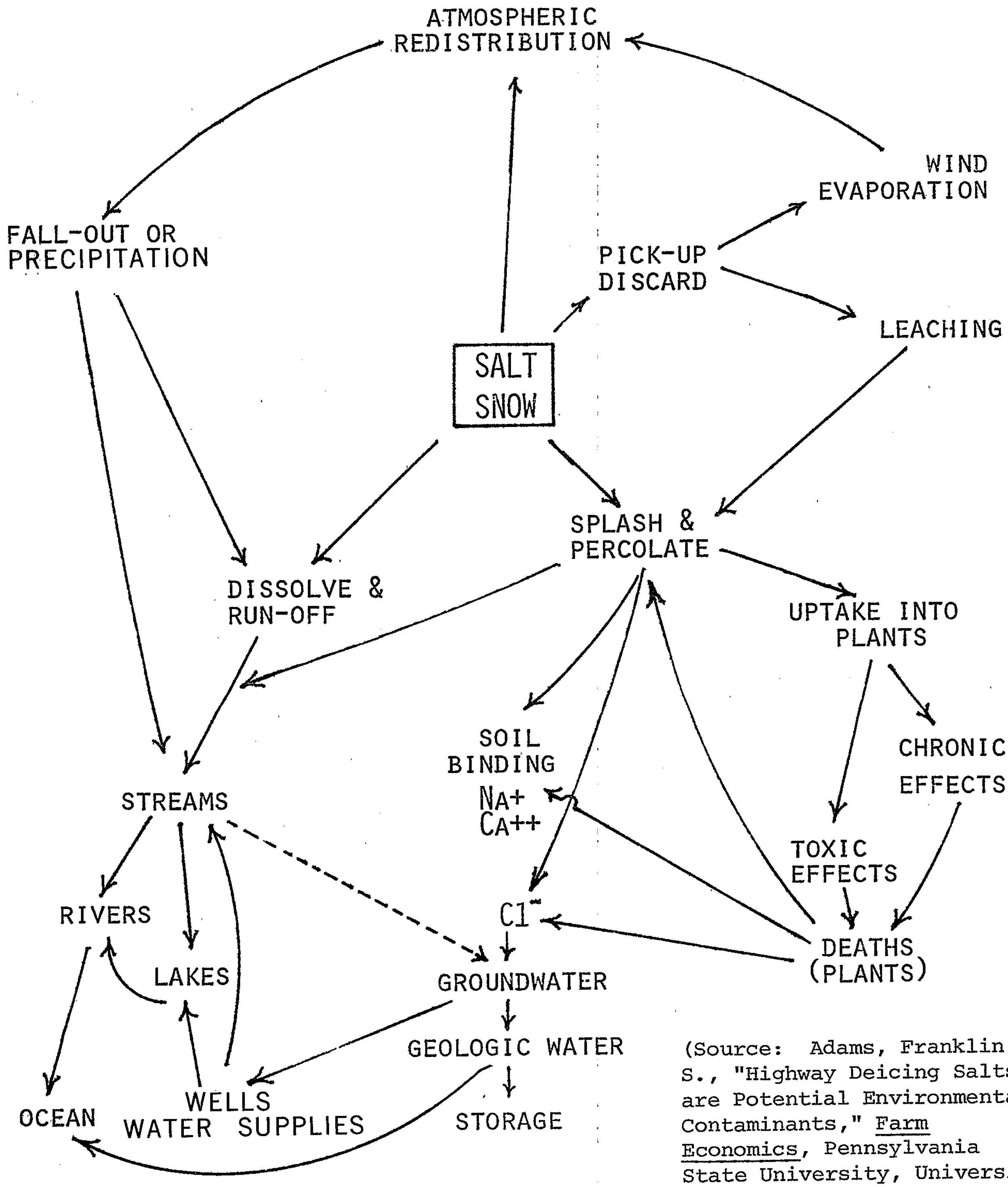
It is essential to have a basic understanding of the paths that salt can take through the environment. All salt applied to the roads will eventually end up in the ocean (or in rare cases in underground pools of water such as fossil geologic water supplies) or will be stored in the environment for an indefinitely long period of time (chiefly in soils). Between the time of its application and the time of its eventual storage, salt is capable of upsetting many ecological balances. Once salt has been applied to a highway, it is dispersed into the environment in a number of different ways. (See Figure 1)

Splash --

As vehicles pass over the salt solution, some of it will be splashed onto the surrounding roadside. The salty water will then percolate downward into the ground. Depending on the type of soil, some fraction of the sodium ions (or calcium ions in the case of calcium chloride) will bind with the soil. The remaining sodium and chloride ions will then be available for uptake into vegetation or will eventually enter into the groundwater supply. Salt solutions may also be splashed directly onto roadside vegetation.

Runoff --

Solutions of highly concentrated salt may also run off the highway directly onto the surrounding roadside causing problems as outlined above, or it may be carried in storm drains or gutters as runoff to another location. Such runoff can also damage vegetation, enter into groundwater supplies, or enter into surface waters, such as streams, rivers, ponds, lakes, and reservoirs. Runoff has been observed with



(Source: Adams, Franklin S., "Highway Deicing Salts are Potential Environmental Contaminants," Farm Economics, Pennsylvania State University, University Park, Pennsylvania (1973).

Figure 1. Fate of Salt in the Environment

concentrations as high as 35,000 mg/l (325), approximately the same concentration as ocean water.

Pick Up and Discard

In many areas salt-laden snow may be scooped up and carried by truck to another location. Large quantities of such snow may contain a great deal of salt. Depositing the snow anywhere other than in the ocean or in an already highly polluted river will very likely lead to severe groundwater damage and/or vegetation decline.

Atmospheric Redistribution

Road salt can enter into the atmosphere via the dispersion of small droplets when cars and trucks pass over roads covered with a salt solution. The larger drops of salt solution, referred to as "splash", will fall out very near the highway (probably within a maximum of about 100 meters). The smaller droplets will evaporate to an equilibrium size consistent with the ambient relative humidity and be dispersed over a large area. If the ambient relative humidity is near 50% or less, the solution droplets will evaporate to a dry salt particle whose very small size will be a function of the highway salt solution concentration. (322) Also the dry salt residue remaining on the highway after the moisture has evaporated can be scattered into the air by the passage of vehicles. Calculations by Stensland (324) have shown that about 1 to 1.5% of the road salt is passed into the atmosphere.

Before turning to the discussion of specific damage, it is important to separate out the effects of road salt from the effects caused by salt spray from the ocean. Analysis of precipitation chemistry data by Stensland (321, 322, 323) has shown that during the winter months in locations where road salt is used, salt water spray from the ocean (larger droplets that fall out rapidly) dominate over road salt spray only in very close proximity to the coast. The affected range is anywhere from a few hundred meters to a few kilometers depending on geographic and climatic conditions, especially wind speed and direction. Furthermore, the atmospheric content of salt particles will be dominated by road salt sources more than 10-50 kilometers from the ocean, the distance again depending on geographic and climatic conditions. Since the amount of road salt and ocean salt in the atmosphere is very small in comparison to the total amount of salt entering into the environment, it must be concluded that in areas where road salt is used, the sea salts become a dominant factor only in very close proximity to the ocean. Examples in which sea salt would prevail are: bridges or other structures which pass over or are directly adjacent to the ocean and which receive salt spray; vehicles which are parked along the ocean front. The conclusion is that for all the areas where road salt is used, sea salt is a significant cause of damage in a very small fraction (1% or much less) of the cases.

In addition to damage to the natural environment, man-made goods also receive substantial damage from road salt. Vehicles passing over the salt solution on the highway receive a spray of a highly concentrated salt solution, depositing the salt on the metal surfaces where it will remain and cause accelerated corrosion. Splash from vehicles and direct runoff can coat highway and surrounding structures with a salt solution, making those structures more vulnerable to corrosion. Seepage of the salt solution through pavement (or cracks in the pavement) will eventually cause damage to the roadway. Runoff and percolation will allow the salt solution to eventually attack underground wires and pipes, again accelerating corrosion and providing problems for industrial users.

4.1 DAMAGES TO NATURAL RESOURCES

Mention of damage from road salt to natural components of the environment has been frequent in the literature. There is an abundance of information on the means by which the damage occurs and numerous reports of specific damage cases and, in some instances, the cost incurred. Nevertheless, the proponents of salt use have continually opposed the significance of such findings and the subject is usually dismissed with responses such as "the value of a tree does not compare to the value of human life." Examination of the literature reveals that damage to vegetation, while extensive and costly, is not the major component. The real concern is over contamination of water supplies and the resultant impact on human life.

In this section, the nature and extent of salt related damage to natural resources will be examined. The fact that there is a link between road salt and damage has been proven throughout the literature. This section serves to summarize the established research.

In general, salt damage to natural resources is usually characterized by the fact that it is either irreversible, too costly or difficult to reverse, or only the passage of time will allow the effects to disappear. There is a significant amount of risk involved when irreversibility is an issue because the true meaning of the damage may only become fully known at a future time, at which point it is too late to make a change.

Assessment of damage to natural resources from road salt has always been a difficult problem. Not all the processes by which damage occurs or the exact relationship between salt use and damage are known, thereby making assignment of damage difficult. The effects of salt in nature are often cumulative and therefore require lengthy studies for complete understanding. Finally, because the concept of irreversibility is so little understood, there is often disagreement over the cost of damaged goods, making it difficult to assign costs. The cost analysis of damage to natural resources which appears in Section 5 is conservative. The cost figures which are developed provide a lower bound; actual costs may actually far exceed these numbers.

4.1.1 Water Supplies (Drinking) and Health

The contamination of water supplies is possibly the most serious damage that results from the use of road salt. Salt can enter into groundwater supplies as it percolates down through the soil. It can also enter into surface supplies as direct runoff from highways. Processing water to remove salt is an extremely expensive and complicated matter, and is therefore rarely done. Typically, the safest means of preventing the salt from reaching water supplies is to catch the highway runoff and direct it to a high flow stream or river which eventually reaches the ocean without entering into another water supply. While provisions for runoff can be provided for new highways, the cost of the provisions must be considered. Such design has not been incorporated into a majority of the existing roadways, and to do so now would be very costly, if even possible.

The concentration of sodium chloride in the groundwater is a function of many factors, most notably: 1) the amount of salt applied to the highway and distance from the groundwater; 2) the type, frequency and quantity of precipitation; 3) the type of soil and geologic material; 4) direction and rate of flow of the groundwater; and 5) the highway drainage design.

The concentration of sodium chloride in surface waters is also dependent on many factors, but primarily a function of: 1) the amount of salt applied to highways which eventually reaches the body of water; and 2) the volume of flow of water into and out of that body. Depending on the rate of flow, some surface waters are able to handle large quantities of salt without a dangerous increase in the equilibrium level of sodium and chloride. Consequently, the effect on groundwater is usually more significant and possibly more serious because of the slow movement of the water involved. While some groundwaters show a significant movement within a matter of months, in some cases the time required for the water surrounding a well field to change may be on the order of years. Consequently, the groundwater sodium and chloride levels typically show a lag in response to the actual date of salt application. Surface waters are generally affected much more immediately.

The reports of infiltration of road salt into drinking water supplies are numerous and growing (see Bibliography - Water). Some of the first cases of serious salt infiltration were found to have been caused by improper salt storage facilities. It was assumed for some period of time thereafter that most salt pollution was the result of poor storage. It has been shown that this is not the case. In fact most salt pollution that is presently occurring is apparently caused by runoff from streets and highways (53, p. 25).

The details of salt contamination in various parts of the country have been extensively recorded. Since the literature is filled with some outstanding works on this subject, this section does not attempt to review or mention all of the findings. However it does contain an updated report on the trends for some of the New England states. The reader who wishes to substantiate the findings should refer to the literature, most notably the work by the Massachusetts Special Commission (4), EPA (15), Terry (53), Hutchinson (95), the Massachusetts Department of Public Health (101), and Motts' (104).

Sodium and chloride content in water is measured in terms of milligrams per liter (mg/l) or, equivalently, parts per million (ppm). Until several years ago, chloride tests were easier to perform than sodium tests and therefore the older literature generally refers to salt in terms of chloride levels. Measurement of sodium in addition to chloride is now universal.

A portion of the sodium entering water supplies through the ground is usually bound into the soil so that not all of the sodium reaches the groundwater. In Massachusetts the ratio of sodium to chloride in most public supplies has been reported to be between 1:3 and 2:3 (53). Thus a water supply which has reached the limit of 250 mg/l chloride may contain between 83 and 167 mg/l of sodium. There are currently no federal guidelines on the allowable level of sodium in drinking water supplies. However for chlorides, the U.S. Public Health Service recommended in 1962 a maximum safe level of 250 m/gl. In 1968, the Federal Water Pollution Control Administration advised a maximum "desirable" chloride level of 25mg/l.

Some of the most recent data on water supplies show that the trends in chloride and sodium content are in most cases still increasing, while in other cases remaining nominally stable or in equilibrium. The accompanying graphs (see Figures 2, 3, 4, 5, 6, and 7) show the latest average trends for four New England States. The sodium content could be estimated at between one-third and two-thirds the level of chloride given in these graphs. Prior to 1940, all Massachusetts data indicated chloride content less than 10 mg/l.

Initial examination of the most recent Massachusetts data (285, 326) reveals that there appears to be a slight decline in the number of communities with one or more public water supplies containing sodium above 20 mg/l:

1970	1971	1972	1973	1974
69	77	96	95	90

However, the figures for 1970-1972 period were established by Robert Terry (53), and there may be a slight difference in the methods of analysis. Also salt storage facilities have been improved over the past few years, possibly accounting for the small decline.

Richard S. Woodhull, head of the Water Division of the Connecticut Department of Health, reports that most water supplies in Connecticut have been

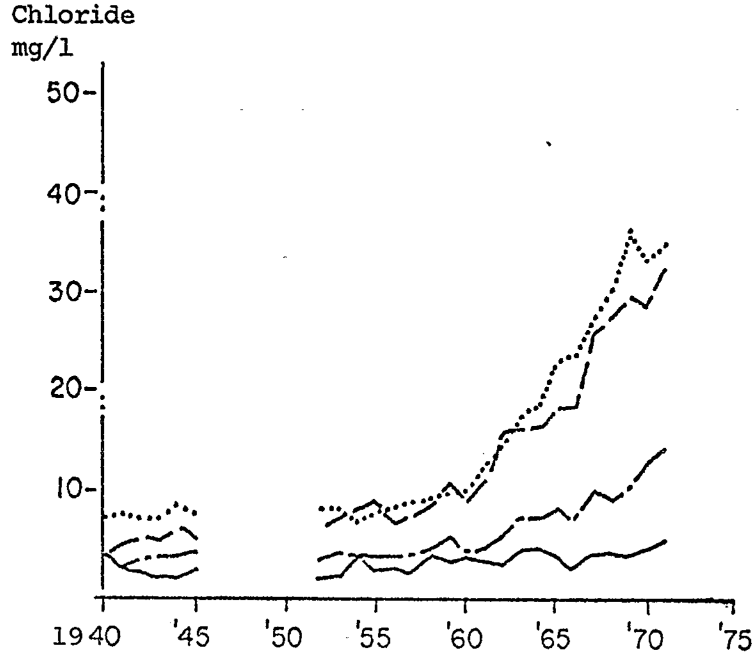


Figure 2. Massachusetts - Ground Waters

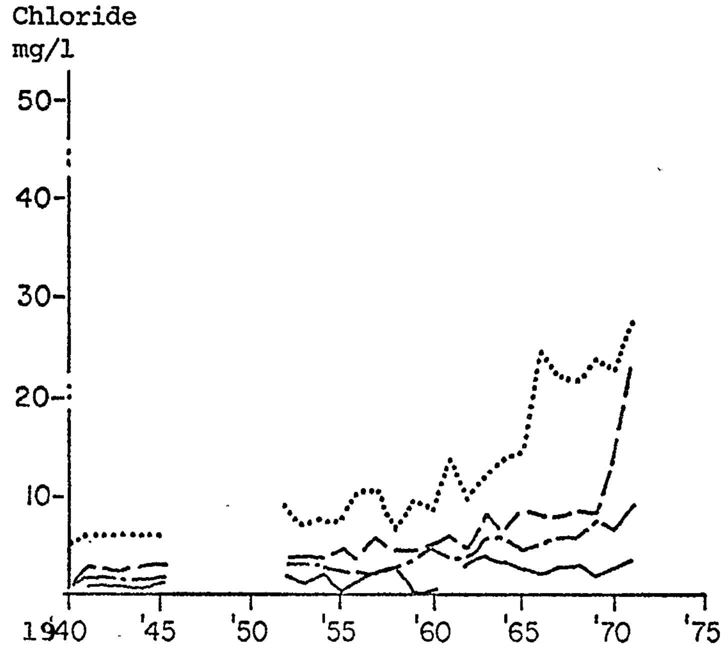


Figure 3. Massachusetts - Surface Waters

Legend

- ··········· 5 - 20 MILES INLAND
- — — — 21-56
- —·—·— 57-100
- ——— >100

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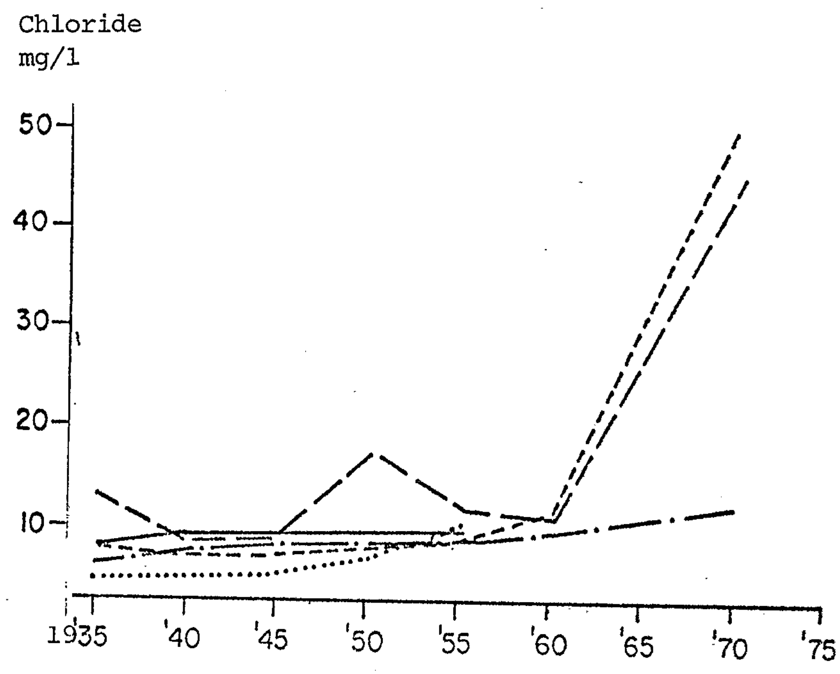

Figure 4. Connecticut Ground Waters

Legend
AVON
CANAAN
DURHAM
ELLINGTON
HAZARDVILLE

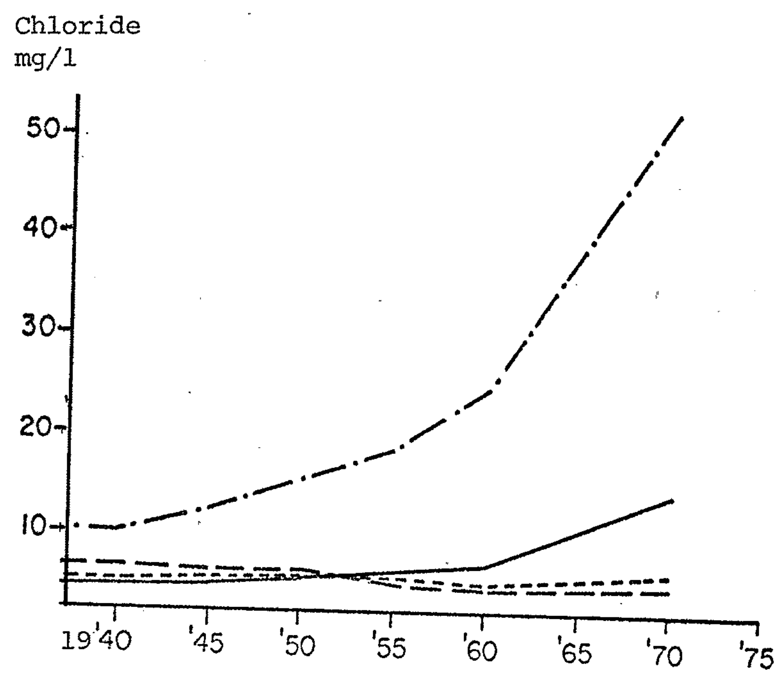

Figure 5. Connecticut Ground Waters

Legend
THOMPSON
WASHINGTON GREEN
WATERFORD
WATERTOWN

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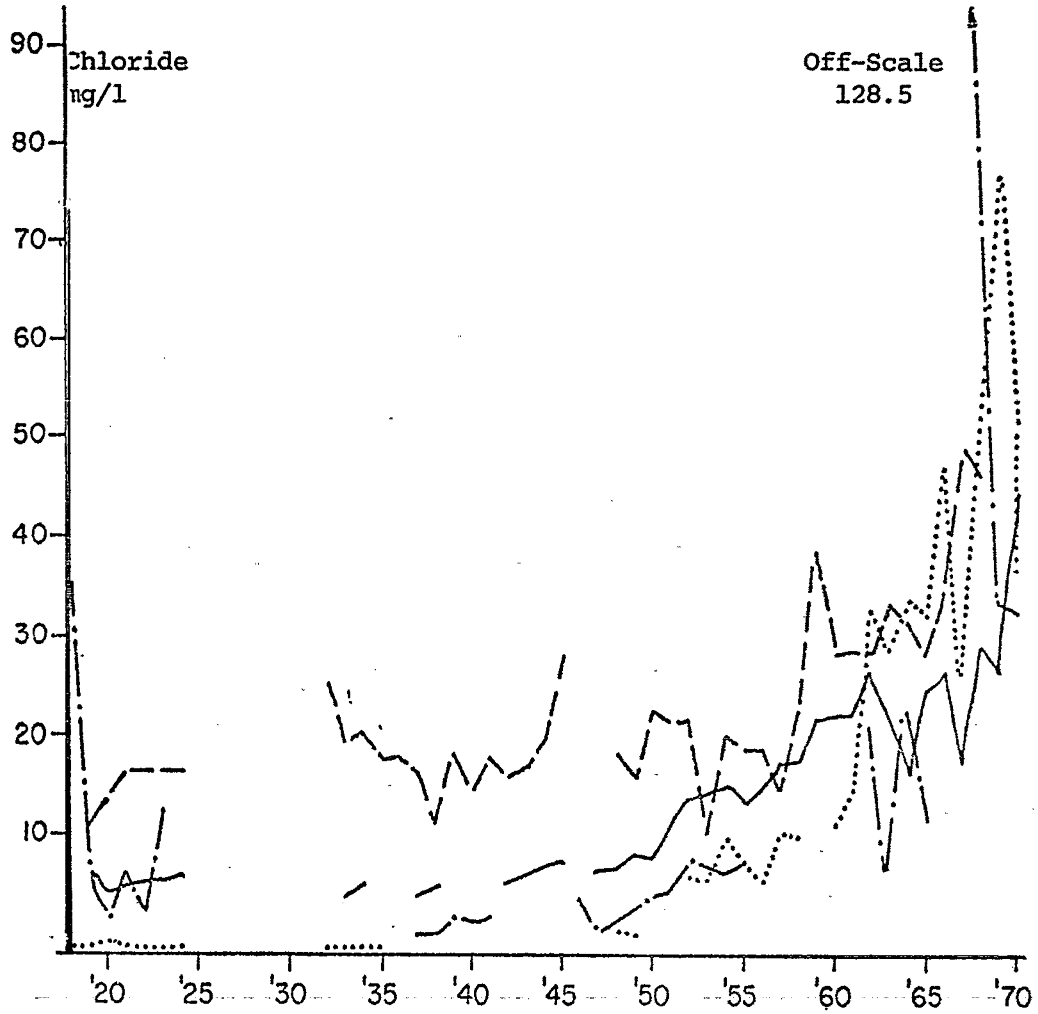

Figure 6. New Hampshire - Ground Waters

Legend

COLEBROOK

DERRY

DOVER

HAMPTON

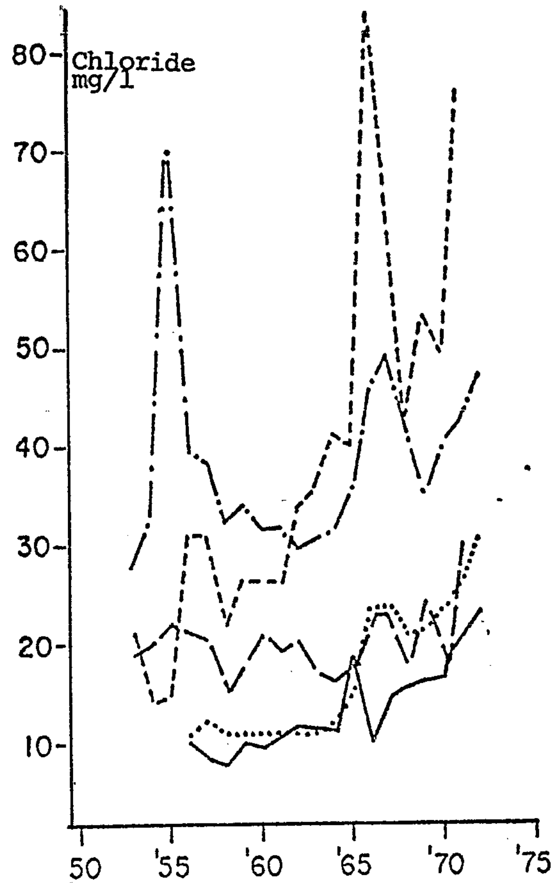

Figure 7. Rhode Island - Surface Waters

Legend

CUMBERLAND HILL

EAST PROVIDENCE

JAMESTOWN

NEWPORT

PAWTUCKET

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showing a continually growing content of sodium chloride*. A few supplies have appeared to level off, probably in response to the 33% cut in the state's use of salt. (This cut was initiated because of salt infiltration. Some cities and towns have followed the state's lead).

In 1964 the State of New Hampshire established the Special Services Division for the purpose of replacing wells contaminated by salt. The budget for the Division had been set at $100,000 for 8 years. In 1974 and 1975, it was raised to $200,000, apparently to cover the cost of increasing well damage.

Although the trends appear ominous, there are many who claim that the current levels of sodium and chloride in the water supplies are not a problem. An early argument was that the level of salt was below the taste threshold, and therefore safe. Such an argument does not consider the fact that there are highly poisonous chemicals which are either tasteless or odorless. The claims by salt interest groups that concentrations of chloride as high as 2,000 mg/l (between 667 and 1,333 mg/l sodium) are not harmful (42) are not supported by experimental data; in fact, the scientific evidence is totally contrary.

For some years now, medical research has established that intake of sodium chloride is a critical factor, affecting many health conditions, including hypertension, cardiovascular diseases, renal and liver diseases and metabolic disorders (135). Intake of salt also presents a danger to a large percentage of pregnant women (135). Consumption of too much salt can generally contribute to hypertension (and eventually congestive heart failure), poor circulation, and stress on the internal organs (132, 133, 134). The most recent research has further confirmed the link between salt and hypertension, and between salt and the other diseases and problems mentioned above (134, 138, 139, 140).

As mentioned earlier, there is no public health standard for sodium in water. However, the American Heart Association (19), backed by many leading medical researchers and physicians, has recommended a limit of 22 mg/l sodium in drinking water for patients whose diets are restricted to less than 500 milligrams of sodium per day (19, 135).** According to recent estimates approximately 23 million Americans are

---

* Personal Communication, July 2, 1975.

**Note for example that a person restricted to 500 milligrams of salt per day who consumes 3 liters of water (including cooking purposes) containing 100 mg/l of sodium will be consuming 60% of his allowed daily intake. Since most foods contain some sodium, it is impossible at this level to prescribe a diet which would supply enough food (natural and unsalted) without causing the person to exceed his allowed intake. (141). The 22 mg/l guideline has been established to allow a patient to maintain an adequate diet.

suffering from hypertension and should restrict their sodium intake (132). This group, together with other persons who should restrict sodium intake to 20 mg/l comprise at least 20 to 25% of the population, with some researchers claiming the percentage to be as high as 40% (138). Unfortunately, many of those who should restrict their salt intake are not aware that their life is at risk and therefore consume much more salt than they should. Therefore for a particular individual, water with a sodium content of more than 20 mg/l may not present a significant danger. However, such water is potentially harmful to those persons on low sodium diets (approximately 4-5%). In addition, further education of the public will undoubtedly result in greater awareness of hypertension and a greater percentage of the population will restrict their salt intake. Since complete reversal of the sodium trends might take years once action is taken, more people are endangered than just those currently on salt restricted diets.

Furthermore, one must consider the remainder of the population which is not yet hypertensive or diseased. Dr. Lewis Dahl, who has researched salt and hypertension for years, has written that heightened intake of sodium from the time of infancy is unhealthy (134). Dr. Lot Page, who has been involved in some of the most extensive studies on hypertension and is currently Chief of Medicine at the Newton-Wellesley Hospital in Newton, Mass., has written that man was not meant to consume salt other than what is to be found in natural food sources and the more salt that is consumed, at all times in life, the higher is the probability of eventual hypertension. Research does show that the consumption of excess salt during infancy may lead to hypertension later in life (140). The two facts that (1) salt has been linked with hypertension and, (2) that blood pressure is the chief indicator of life expectancy (for both physicians and insurance companies) can lead to no other conclusion than road salt pollution of our water supplies is presently a highly dangerous situation. While the use of salt on food is optional, consumption of salt in the water is obligatory. Most serious of all, the presence of sodium in water is unknown to most of those who consume it. Dr. Lewis Dahl and Dr. Lot Page have both stated that the infiltration of road salt into our water supplies is a very serious and urgent problem.*

4.1.2 Other Water Resources

Examination of the literature has shown that deicing salts** usually have very little effect upon large rivers and streams. Because the rate of flow is so large, especially during the spring thaw when the bulk of the salt is released into the river, the sodium chloride is substantially diluted. Large rivers rarely show an increase of more than 10 to 20 mg/l of sodium chloride (91, 93, 108).

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* Personal Communication, June 10, 1975 and June 11, 1975 respectively.

** Primarily sodium chloride with the rest calcium chloride.

Smaller streams and brooks may be much more seriously affected depending on their flow rate and the amount of highway runoff. During a study of the Irondequoit Bay Drainage Basin in Monroe County, New York, it was observed that the principal input to the Bay, Irondequoit Creek, reached a winter maximum of 670 mg/l chloride. Maximum concentrations in ten small creeks were found to range from 260-46,000 mg/l chloride during the winter (73, 80).

The final destination of such streams must be examined closely in order to determine the resultant effects. For example, Diamond Lake in Hennepin County, Milwaukee, Wisconsin was reported in 1970 to contain the equivalent of 3,780 mg/l sodium chloride (48). Undoubtedly in some cases the effects on aquatic life in the receiving bodies may be serious. It has been observed that heavy flow of salt may prevent complete mixing and prolong stratification of the water. Such extended stratification can result in oxygen deprivation in its lower depths and has caused death of organisms living in the lower depths. Since these animals are an important link in the food chain, fish kills have resulted (89, 97). The use of road salt has led to similar but less serious damage in Irondequoit Bay, Rochester, New York. If salting continues at the current level, serious damage may occur when the dissipation of salt in the drainage basin reaches a steady state of equilibrium. In discussing the potential effects of salt on lakes and ponds, Adams stated that, "...it is well within the realm of possibility that the addition of significant amounts of salt could contribute to the biological process of aging in lakes called eutrophication." (1)

Other studies have shown that under special conditions, the entry of road salt into freshwater can cause mercury and other toxic heavy metals to be released from contaminated sediments (82). Release of these metals in ponds, lakes or reservoirs that do not have a high inflow/outflow rate might present a serious hazard to the aquatic and human life.

4.1.3 Soil

While discussion of damage to roadside soils may seem unnecessary in addition to an examination of vegetation and water damage, it is indeed an element of the environment which is very definitely degraded by salt. High concentrations of salt in the soil will not only lead to the death of existing vegetation, but in many cases will also lead to an almost irreversible situation in which proper drainage is seriously affected and only a limited variety of vegetation, if any at all, may grow in the soil.

Sodium and calcium chloride are highly soluble in water and easily disassociate into sodium, chloride, and calcium ions. The chloride ion, having a negative charge, is repelled by the negative charges of clay and other organic colloids and therefore is easily leached out of the soil by water passing through. However, the positively charged sodium and calcium ions are attracted to the negatively charged clay and other colloidal soil particles (20). Thus, depending on the type of soil, amount of salt applied, and the amount of water leaching through the soil, as a result of precipitation, a substantial percentage of the sodium and calcium ions may be retained. The high sodium content may result in a number of undesirable soil properties, especially loss in permeability (24, 199). In addition the presence of the sodium will lead to the leaching of other positively charged ions such as potassium, calcium and magnesium which are essential for plant growth (20). All of these factors can result in a poor roadside environment for vegetation growth. Depending on the severity of the situation, it may take many years for the sodium to leach out into the groundwater, rendering the soil useless to all but a few hardy varieties of vegetation, such as high salt tolerant grasses. Loss of vegetation has in some cases led to severe soil erosion; and the high soil content runoff has clogged drain sewers (155).

As expected the highest salt content in soil is generally found near the highway and near the ground surface. Concentration generally decreases with depth and distance from the road surface. Some salt in soil has been found as far as 30 meters from the road but usually the concentration is significantly decreased at 7 to 18 meters from the highway. (This does not include situations where runoff is collected and diverted to other locations, of course.) (24, 96, 199) In addition, studies have shown that roadside soil concentration of salt increases with the number of years salt has been applied (193). The implication of this finding is that application of road salt has a cumulative effect on the roadside soil. Continued application of road salt will very likely increase the salt concentration to the point where eventually the soil will be highly alkali and possibly unfit for most vegetation.

Studies by F.E. Hutchinson under a cooperative program between the Maine Agricultural Experiment Station and the Maine State Highway Commission have shown that high rates of application of gypsum (3 kg/square meter) to roadside soils can lead to a reduction in sodium in the topsoil. (Reduction of sodium in the subsoil has not yet been proved.) (195, 196, 197) While these findings provide some encouragement, the cost of the gypsum application must be considered.

4.1.4 Vegetation

Sodium chloride applied to highways to aid in ice and snow removal has a significant effect on the decline of roadside trees and vegetation. While drainage conditions are an important factor in determining the distance to which vegetation is affected, most damage occurs within 9 meters of the edge of the highway. Other factors such as drought low soil fertility, low soil permeability, air pollution from vehicle exhaust, and mechanical injury to roots also contribute to the damage (175). However, in-depth studies have shown that salt in many cases is the prime factor leading to death of vegetation (20, 156, 157, 174). These studies were based on soil samples and analysis of sodium and chloride content in leaf and twig samples. One study clearly demonstrated the effect of salt by comparing tree damage on salted and unsalted roads within the same towns (175).

The most susceptible trees are the broad leaf types such as sugar and red maples, linden and black walnut, and conifers such as red and white pines, Colorado spruce, Douglas fir and hemlocks (24,41). Some of the most extensive studies on salt damage have been done at the Virginia Polytechnic Institute (20, 160). This work plus several other works (24, 157) (also see Bibliography-Vegetation) support the findings in the following paragraphs.

The major portion of salt damage to vegetation is caused by uptake through the roots, rather than by splash or spray onto the leaves or needles. Sodium and chloride content in the vegetation has generally been found to be a function of the sodium and chloride content in the soil. The degree of salt injury is typically related to the chloride more than the sodium level in the plant. Contrary to earlier theory, salt uptake into plants can occur during winter months, even though the plant may appear dormant, and salt infiltration can occur even in frozen soils. Yearly application of salt to highways can lead to a toxic accumulation of sodium and chloride in the plants. Woody perennials are unable to release the salts back into the soil, except by leaf loss and dying branches, an inefficient means of recovering from salt accumulation. In general, young trees absorb more chloride than older trees and substantially more sodium than older trees. Different plant species vary in their sensitivity to sodium and chloride, dependent mainly on absorption rates and tolerance. The usual sequence of events in salt damage to vegetation is increasing sodium and chloride concentration in plant tissue, reduced growth, falling leaves, dropping twigs, dying limbs, and eventually plant death.

One researcher found in controlled experiments of salt effects that "once foliar symptoms of salt were noticed, it was not possible to prevent further damage -- the tree always died even though they were taken off the salt solution and given only pure water."*

The reports of salt damage to vegetation are extensive as the literature has shown. Unfortunately, assessing the true magnitude of the problem approaches the impossible. Nevertheless it seems safe to conclude that under average roadside soil and drainage conditions, light to moderate salt usage (5-10 tons of salt per lane mile per season) will lead to a small but noticeable vegetation decline, depending on the variety of vegetation. Heavy use of salt (15-25 tons per lane mile per season, or more) may lead to extensive vegetation death and may eventually allow growth of only very hardy alkaligrass.

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* Personal correspondence from Clinton E. Carlson, Plant Pathologist, Forest Environmental Protection, State and Private Forestry, December 18, 1974.

Heavy salt use and the resultant damage to vegetation can lead not only to personal property damage and possibly some crop damage, but also to the creation of unsightly conditions along the highway, reducing the property values and negating the highway beautification programs. Although difficult to assess, there are real costs involved in terms of increased highway maintenance for removal and replanting.

4.1.5 Fish and Wildlife

The literature contains a few reports of death of fish and wildlife attributed to salt (15, 48). While there has been a small amount of research on short-term toxic levels of salt, there is little known about the long-term effects of less toxic levels. Until further research is carried out, it is not useful to speculate on the possible extent of the damage. However, it is probably fair to state that bodies of water which have significantly increased levels of sodium chloride due to road salt runoff will demonstrate noticeable changes in their ecosystem. Such changes are unlikely to be beneficial.

4.2 DAMAGE TO MAN-MADE GOODS

The mechanisms by which salt damages man-made goods are described in this section. Claims and accounts of salt-related damage, predominantly to bridges and automobiles, are numerous. The literature presents sufficient evidence to directly link the damage to deicing salt use. Reports of public officials as well as professional engineers and concerned citizens leave no room for doubt as to the nature or extent of the damages.

Such damage is more easily observed than is the damage to the natural environment. A sampling of some of the specific reports is presented. Section 5 will present an economic assessment of the damage caused by deicing salts.

4.2.1 Corrosion of Motor Vehicles

It is likely that more people have directly observed vehicular corrosion than any other form of salt-related damage. The link between the application of salt on highways and the corrosion of automobiles is well documented (see Bibliography). This section of the report will discuss the corrosion process and examine parts of the automobile susceptible to it. Section 5.5 contains an economic analysis of the probable costs of this corrosion.

The Corrosion Process --

The corrosion of steel is an electrochemical reaction in which iron is oxidized to the ferric state. In the presence of moisture and atmospheric oxygen, the free energy of the reaction is such that iron is spontaneously oxidized to form the insoluble hydrated ferric oxide (rust). This is the typical reaction occurring in the near neutral environment of auto body steel. When acids are present, oxygen is not required and the iron is first oxidized to the ferrous ion. This ion can be further oxidized to the ferric state and react with hydroxyl ions to form ferric oxide. Both reactions (with water and oxygen or with acid) can be prevented by eliminating contact between the metal surface and any of these elements. This is the motivation behind such rustproofing procedures as painting and asphaltic coating of steel. Galvanizing sheet steel protects the steel for a longer period of time because zinc is electrochemically more active and is thus oxidized in preference to the iron. Dipping steel in a zinc rich paint initially protects it by preventing moisture and oxygen from contacting the surface; and offers further protection though preferential oxidation of the zinc. Unlike aluminum, an exterior layer of oxidized steel offers no protection from further oxidation and in fact may accelerate the corrosion process.

Because steel is not a homogenous, cyrstalline product, there are small differences in surface composition in ordinary sheet steel which can cause minute electrical potentials to develop. Further exacerbating this tendency is the presence in motor vehicles of other metals, spot welds, and stresses from metal forming. In contrast to the general, overall even oxidation that will occur in untreated steel in the presence of moisture and oxygen, minute electrical potentials in the steel itself result in the potentially more serious pitting corrosion. Pitting is attributed to differential oxygen concentrations at the metal surface. Those parts in contact with oxygen become cathodic with respect to oxygen deficient areas. In cathodic regions hydroxide ions are produced, while in the anodic regions iron goes into solution as the ferrous ion. It is in the anodic regions, which are protected from oxygen by paint, undercoating or other layers of steel, where the serious pitting takes place. This has led some experts to question the wisdom of protective coatings, unless they can be so thorough as to prevent any contact with moisture and oxygen. Even totally protective coatings may be subject to attack by vibration at joints.

A number of other parameters have been shown to effect corrosion rates including temperature, the presence of electrolytes, and the removal of corrosive products from the anodic and cathodic regions. Chemical reactions are temperature dependent; the rate of reaction approximately doubles for every 10°C rise in temperature. Electrolytes such as salt, fertilizers and the soluble products of atmospheric pollution accelerate the corrosion process by facilitating electron transfer. It can be inferred that autobody steel will corrode most rapidly when protection from oxygen is only partial, and when it is placed in a warm, humid environment in the presence of neutral or acidic electrolytes.

<u>Experimental Evidence of Auto Corrosion</u> --

A series of experiments that have sought to define the role of deicing salts in the corrosion of automobiles was initiated in the mid 1950s in response to the unprecedented corrosion that was being observed in and around headlights, wheel wells and door panels on the new cars of that era. These field tests are discussed below with respect to the parameters assessed.

Atmospheric Conditions --

Relative humidity has a significant effect on the oxidation of many metals. Condensation on metal surfaces will tend to occur at relative humidity levels far below 100% due to impurities on the metal surface or in the atmosphere. Reports from Switzerland, Germany and Canada (206) indicate that when the relative humidity exceeds some critical value ranging from 60% to 75% the corrosion rate is markedly increased.

Increasing attention has been given recently to the role of atmospheric pollutants in the corrosion process. Craik and Yuill (206) found the atmospheric corrosion rate to be higher in the city of Winnipeg, Canada, than in the surrounding suburbs. Atmospheric corrosion rates in eight different areas across Canada were measured by Fromm (205) by attaching test metals coupons to automobiles. Conditions in these areas ranged from very dry to very humid; from coastal to inland; and exhibited a wide range of atmospheric pollutant concentrations. In high density areas where the atmosphere contains large concentrations of sulphur dioxide, the corrosion rate is approximately four times that of rural areas. Corrosion rates are also markedly increased when in proximity to a large body of salt water.

Deicing Salts --

Several experiments have sought to quantify the partial effect of deicing salts on the corrosion rate of automobiles. In the investigation by Fromm (205), traffic simulator tests performed with and without deicing salts indicated that salts and atmospheric pollutants each increased the corrosion rate by approximately the same amount in the Toronto area.

In the test sponsored by the Research Foundation of the American Public Works Association (APWA) (209), three groups of automobiles were driven over controlled road sites in the Minneapolis suburbs for three winters. The partial effect of atmospheric pollution in this region was measured by test coupons attached to automobiles (where the combined effect of atmospheric pollution and salting would be measured); and other coupons placed in the vicinity, but removed from deicing salts. While the fraction of the corrosion rate attributed to salt varied from 15.9% for a spring exposure to 65.2% for a winter exposure, the report concluded that a likely figure for the area was approximately 50%.

The principal difficulties associated with using the APWA study to project national corrosion estimates attributable to road salting are (1) climatological and atmospheric variation is lacking due to testing in only one location, and (2) an ordinal index of severity (0,1,2) was improperly used to compute a cardinal measure of percent corrosion attributable to salt. Additionally the use of only one make of automobile (1968 Ford Falcons from the Kansas City production line) may have produced biased estimates if this make and vintage is not representative of the "typical" automobile in use.

In a related test sponsored by the National Association of Corrosion Engineers (NACE) (207), electrical resistance probes were attached to automobiles in 14 different cities. The experiment was designed to measure the partial effect of deicing salts and reached similar conclusions to those of the APWA study. No attempt was made to statistically analyze the separate impacts of atmospheric pollutants, humidity, temperature, and the use of deicing salts on the measured corrosion rates. Such an analysis would be highly desirable but is not possible because of gaps in the data caused by failure of certain probes.

In the APWA-Salt Institute test (209), and in earlier experiments in Canada and Europe, various chemicals were tested for their effectiveness as corrosion inhibitors. Typically the chemicals were mixed with the salts before application to highways. Corrosion inhibitors were shown to have very limited potential in reducing salt induced corrosion of automobiles. In addition, they posed serious adverse environmental consequences such as the health endangering effects of hexavalent chromium (15).

Other Factors --

Storage of an automobile in a closed, heated and poorly ventilated garage during the winter may exacerbate corrosion in areas where snow, ice, and deicing chemicals have been deposited. The apparent explanation for this circumstance is, as mentioned earlier, that chemical reactions are temperature dependent.

The corrosion rate of an automobile is significantly affected by the shape and construction of the automobile body. Of particular importance are those steel surfaces accessible to moisture, oxygen and electrolytes. Since pockets which collect dirt and debris tend to retain moisture long after other surfaces have dried out, they are sites of the most severe corrosion. Felt, fiber glass, rubber and other materials that tend to retain moisture accelerate the corrosion process when in contact with steel.

Areas Affected by Corrosion in Vehicles --

The safety and the economic value of an automobile are adversely affected by corrosion in three main areas: the chassis and box sections, the braking system and the electrical system. The most visible effects of corrosion occur in the box sections which are made up of thin steel sheets connected by welding. Structural weakness caused by corrosion of the chassis and box sections reduces the protection offered by the automobile in an accident. The corrosion of floor panels eventually allows exhaust gases to enter the passenger compartment. For automobiles manufactured with unitized body construction, the replacement of a corroded section frequently costs more than the value of the car.

The most vulnerable parts of the braking system are the hydraulic brake lines. These lines are quite thin and are exposed to moisture, salt and other electrolytes, and oxygen. If pitting corrosion is initiated, perhaps because of partial protection offered by rubber mounts, the ultimate consequence can be serious. The semi-permanent rusting-in-place of items such as wheel lug nuts, spark plugs, brake drums and exhaust system clamps, accelerated by exposure to deicing salts, makes work on these parts much more difficult and thus increases the costs of repairs. Performance of the electrical system is also adversely affected by corrosion. Failure of headlights and turn indicators is a frequent consequence.

There is evidence that corrosion is initiated on the exterior of the exhaust system as well as from the interior, and that deicing salts are one of the factors causing this external corrosion, in combination with humidity and temperature. In the snow belt, Midas Mufflers Inc. found that non-galvanized mufflers lasted an average of 18 months and that galvanized ones lasted 24 months. Outside the snow belt the typical life of a galvanized muffler is 48 to 60 months.* The two-fold increase in muffler life away from the snow belt (and deicing salts) may imply a strong role for deicing salts in the exhaust system corrosion process.

There has been a variety of damages reported by highway engineers. Vehicle corrosion for maintenance trucks rates high on this list of associated damage for which costs are incurred by the public at large. In Lancaster, Pa., reports one survey respondent, "The beds of all pick-up trucks become corroded and eaten out very rapidly. Despite constant washing of the beds the chemicals become lodged between the wooden bed and sides of the truck body. In less than two years the sides of the truck body become eaten out."+

According to the same individual, "Another frequent repair is with brakes and hydraulic brake lines of trucks with salters mounted on them. The salt becomes embedded in the brake shoe adjusting mechanism and corrodes the surface to a point where complete dissassembly of the brake is necessary. The hydraulic brake lines that are fastened with clips to the body for support become corroded and require frequent replacement."‡

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* Per spokesmen of Midas Mufflers, Inc. and A.P. Auto Parts.

+ Lancaster, Pa., respondent to Highway Department survey.

‡ _Ibid._

A spokesman for the New England Telephone Company indicated that rust is a greater problem than mileage in terms of maintenance on their fleet of 9,800 vehicles. Despite salt preventive measures taken by the service department -- rust proofing, patching, and washing the vehicles on a regular basis -- their sedans are held for only two or three years and their trucks for four or five years, compared to a nine year average life expectancy for Southwestern Bell, Texas* fleet vehicles. These vehicles remain in service almost a decade despite their exposure to sea salt spray along the gulf coast and some deicing salt use for icing conditions in the pan handle area. This clearly illustrates the impact of continued use of high volume chloride salt on the utility companies maintenance costs. Of course these increased costs of providing service will be passed directly on to the consumer.

An unusual extension of highway department maintenance problems related to salt use occurred in Saginaw, Michigan, where the "in-floor radiant heating system in the main storage garage deteriorated in approximately five years due to salt runoff from vehicles." The only available means to correct this difficulty was to "replace the heating system with overhead gas blowers (at a cost of $18.5 thousand)".+

4.2.2 Damage to Highways and Highway Structures

There have been many claims of salt-related damage to highways, bridges, and other highway structures. A thorough research of the literature and a survey of all snow-belt state highway departments and approximately 100 large city highway departments have disclosed that there has been extensive salt-related damage to bridge decks. By comparison, damage to highways in general has been small. There were only a very few reports of damage to other highway structures. Apparently guard rail deterioration can be a problem, but frequent painting seems to prevent the deterioration. No cost data could be obtained on this added maintenance.

In this section, the process by which bridge deck damage occurs is explained. This process has been verified by many sources. (See Bridge references in Bibliography.)

Damage to Bridges --

Bridge deck deterioration ranks high among major maintenance problems on our nation's highways. The most common forms of deterioration are cracking, scaling, and spalling. Cracking is not considered to be a very serious problem, although it can lead to the formation of potholes.

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* Paul Le Blew, Southwestern Bell, San Antonio, Texas, in a telephone call 6/19/75.

\+ Respondent, Saginaw, Michigan, Highway Department questionnaire.

Scaling is principally a surface phenomenon and is largely eliminated by the use of high quality, air-entrained concrete and the periodic application of linseed oil. Spalling produces cracks and potholes and is serious and difficult to control. In addition, the supporting structure for the bridge may be significantly damaged.

The Nature of Cracking and Scaling --

In bridges, cracking may be caused by (1) shrinkage of concrete due to excessive evaporation rates during the drying process; (2) design features associated with dynamic tensions and flexing in the bridge which result in material fatigue; (3) inadequate materials, especially the use of improper material ratios in mixing concrete; (4) faulty construction techniques; and (5) various environmental factors such as weather, moisture, and the loads carried. With proper attention to design, materials, and construction, cracking may largely be controlled. Scaling is a surface phenomenon that can be caused by freeze-thaw action in the absence of deicing salts. Scaling has also been observed in salt contaminated concrete surfaces not subject to freeze-thaw action, such as the underside of the Biscayne Bay Bridge and Key West bridges in Florida. Scaling is most severe when concrete is subject to freeze-thaw cycles in the presence of saline contamination. (226).

The process of drying ordinary concrete produces small capillary cavities. When water saturates these cavities in the concrete and is frozen, the freezing action alone can cause scaling as the volume of water in the capillaries expands by about 9%. This expansion frequently causes a flaking or scaling of the thin layer of concrete over the cavities.

Air-entrained concrete in part prevents this scaling. Air entrainment is produced by incorporating large air bubbles in the concrete as it is produced. Since water preferentially seeks smaller capillaries, these large cavities remain relatively dry in water saturated concrete and provide a point for pressure relief when freezing temperatures are reached. In a systematic test of 110 different coatings (235, 244), linseed oil treatments were found to be one of the most effective and economic means of preventing scaling when applied to air entrained concrete.

Salts provide more moisture on the surface of the pavement by lowering the freezing point of water. They also create additional freezing below the pavement surface. This latter phenomenon, known as thermal shock, occurs when heat is absorbed from the pavement as ice goes into solution.

Spalling --

Spalling is the process by which the pressure from rusting reinforcing bars cracks a concrete cover. (See Figure 8). The preponderant amount of deterioration from spalling is associated with the use of deicing salts and ocean salt sprays. The corrosion process of reinforcing rods, which deicing salts accelerate, creates a pressure of about 280 kg/sq. cm. (4,000 lbs/sq. in.) easily sufficient to crack the concrete cover over the rods (231). Inspections of bridge structures have revealed that

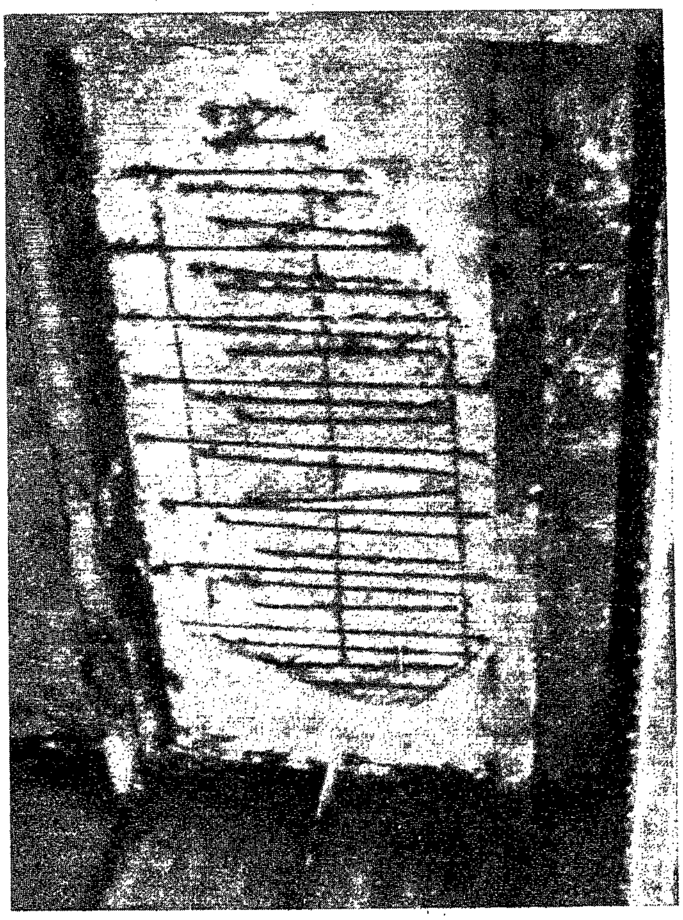

Figure 8. Example of Deck Spall on underside of West Side Highway
(Photograph courtesy of Department of Highways, New York City)

transverse cracks in concrete may result from freezing and thawing in the presence of saline contamination. Transverse cracking in freshly poured concrete is frequently observed as the deck moves under the weight of the concrete, and as the concrete slowly settles around the reinforcing steel. An effective means of closing these incipient transverse cracks is the revibration of the concrete several hours after it is poured (226). Transverse cracks may also be caused by too shallow a concrete cover over the rods and by shrinkage during the drying and curing of the concrete. Such cracks provide access to moisture which then can attack the underlying steel. The rust process is greatly accelerated by the presence of salts and air along with the moisture. Experiments by Berman (212) indicate that pH reduction may be a contributing factor in steel corrosion. Reinforcing steel is typically protected in chloride free concrete because of the high pH of the soluble calcium hydroxide originally present in the cemet. This high pH induces the formation of a protective coating of ferric oxide on the surface of the steel.

Because of the porous nature of the concrete, rusting of reinforcing steel can take place without preliminary cracking since saline solutions will slowly penetrate the concrete cover. It has been found that the chloride ion concentration around the reinforcing steel is reduced by approximately one half for each additional inch of concrete cover (236).

Age of concrete before exposure to salt solutions is an important factor in inhibiting corrosion. It has been observed that bridges built before the 1940s, when salts were first used extensively for deicing, have in many instances survived better than newer bridges. This may be attributed to the substantial length of time required for concrete to properly cure, though it may also be partially explained by a process of "natural selection" and examples of superior workmanship and materials.

Advanced cases of spalling on a bridge deck are easily detected by the presence of large potholes on the surface. These cracks and holes can cause discomfort and reduce the safety of passing motorists and cause damages to automobile shock absorbers, bearings, and ball joints. In infrequent instances, reinforcing steel is corroded to such an extent that a bridge is incapable of carrying its designated load. Less advanced cases of corrosion can be detected by a variety of techniques including electrical potential measurement to pinpoint the corrosion site (236).

Repair Techniques --

Accepted methods for repairing bridge deck spalling involve temporary patching of holes, partial restoration of the deck or replacement of the entire deck cover. Patching of holes without removal of cracked and salt contaminated concrete is an unsightly and usually only a temporary means of repairing spalled sections. A large fraction of patches made in a freeze-thaw environment will fail in less than a year. Many of the potholes form during the winter months, a time when patching is more difficult and driving hazards greater than during the summer. Maintenance patching, even when properly done, may be less desirable than other methods of repairing damaged bridges. Although highway departments view the dollar outlay for maintenance patching as minimal, the full social costs including safety hazards, damages to vehicle suspensions, and traffic delays must be considered.

Partial restoration involves devising more permanent patches, with estimated life of about 15 years, by removing the concrete surrounding the corrosion site. The resulting hole is patched with Portland cement concrete, or epoxy concrete when the speed of setting is important to minimize traffic delays. The surface is sealed and an overlay of asphalt concrete is applied. The practice of sealing the surface of partial restorations also has been questioned by Kliethermes who feels that such deck covers may accelerate corrosion in previously undamaged sections of the deck (230).

Unfortunately removal of active corrosion regions usually is not sufficient to halt the corroding process, and other sections may begin to spall soon after the repair is completed. Formerly passive sites can quickly switch to being active sites as electrons flow to the sections having the greatest positive potential in the deck.

Replacement of an entire bridge deck is an expensive process with repair costs reported between $400,000 and $1,200,000 for large bridges, and is normally justified only when the spalling damage is extensive. Most bridges do not remain part of the highway system for a period as long as 50 years. Partial restoration seems to be more desirable when the time value of money is considered, since expenditures 15 to 30 years from now should not get equal weight in a comparison with outlays today for replacement. Until complete replacement is possible, Kliethermes (203) advocates temporary cold mix bituminous patches on bridges which exhibit active corrosion on 50% to 100% of the deck. For decks where 20% to 60% of the structure contains corrosion sites, concrete removal and patching of chloride contaminated areas is recommended. For bridges containing active cells in 25% or less of the deck, he suggests removal of chloride contaminated sections followed by placement of a waterproof membrane and an asphaltic, concrete wearing course. These recommendations are based primarily on economic considerations.

Deck seals are commonly used in replacement of existing decks and on new decks. In Europe, the use of waterproof membranes, designed to prevent the intrusion of moisture and salts to the reinforcing steel has gained widespread acceptance for new construction and for the repair of existing bridges (233). Many different materials have been used as membranes including: copper sheeting, butyl rubber sheeting, bitumen-aluminum sheeting, bituminous felt, and adhesive coated polypropolene fabric. Dissatisfaction with these methods has led to experimentation with epoxy resins and polyurethanes. In the United States prior to 1970, membranes were frequently produced on site by applying several coats of a coal tar pitch to the concrete surface, and sandwiching a layer of glass fabric between coats if reinforcing is desired. The ability of the membrane to reseal itself in periods of warm weather significantly adds to its waterproof qualities (238). In Europe and in the United States, preformed sheet type membranes are more commonly used now. Over both types of membrane an asphalt wearing course is applied.

Experience with membranes indicates that they frequently do not perform as well as anticipated. Membranes are hand placed and as such are subject to poor workman performance. Additionally, the application of hot asphalt may melt the membrane. In situations where the grade exceeds 4% or there are centripetal forces from curves and braking, the asphalt overlay tends to slide across the membrane. This limits the situations where membranes may be successfully utilized. The typical membrane leaks after a few years, though still offering some protection to the underlying steel.

A number of other procedures to inhibit corrosion of reinforcing steel have been tried, including various coatings applied to the steel before placement. Although many different coatings - including asphalt epoxy, epoxy, nickel, copper and zinc all have been used in experiments, the epoxy coating appears to have the greatest promise (234). Epoxy coated steel is approximately twice as expensive to place as ordinary steel, and results in an increase in total cost comparable to the waterproof membrane. Special tests have been designed to insure that the coated reinforcing rods will not (1) allow passage of chloride ions to the steel, (2) suffer cracks in the coating when bent at an angle of 120°, or (3) abrade during placement.

Cathodic protection is an experimental method of preventing the destructive flow of electrons necessary for the oxidation of reinforcing steel. It has been shown to be capable of halting corrosion in decks already thoroughly contaminated with chlorides. In a paper delivered at the 1975 meetings of the Transportation Research Board, Harold Fromm, of the Ontario Highway Department, described the results of continuing experiments with cathodic protection. Following upon Stratfull's pioneering work, bridges were protected by placing graphite anodes in the deck, covering them with asphalt concrete, and applying approximately 3.23 milliamps of current per square meter. Preparation of the deck in this manner took approximately two days and resulted in minimal traffic disruption. Power requirements for the entire bridge are approximately 1.5 watts per hour, and were so low that the power company considered it not worth installing an electric meter. Actual costs of cathodic protection were $96.82 and $39.37 per square meter on the first two bridges, but were expected to fall to only $9.25 on the fourth installation. The general feeling is that cathodic protection is best applied to bridge decks that are still in sound condition, and that badly deteriorated decks are best replaced.

Experimentation with the composition of concrete dates back to at least the 1940s. Since that time, a latex modified concrete (Dow SM-100) has been marketed for patching bridge decks. The repairs have performed well and the Federal Highway Administration is now using this concrete for overlayment on some bridges. In the early 1960s, silicones were investigated as an admixture to prevent scaling (220). The FHWA is currently studying the feasibility of impregnating concrete with polymers (212). In this process, which is being field tested by the U.S. Bureau of Reclamation in Denver, dry heat is first applied to a deck. Next, approximately 1/2 cm of dry sand is spread and saturated with liquid monomers (typically lucite or methyl methacylate). The sand appears to significantly aid penetration, which is carried to a depth of about 2 1/2 cm, and leads to uniformity in application rates on uneven surfaces.* Finally the monomer is polymerized in situ with heat. Polymer impregnated concrete has many advantages over ordinary concrete. It is impermeable to chlorides, improves abrasion resistance by providing a harder surface, and has greater freeze-thaw resistance. It is unknown at this time how resistant the new concrete will be to cracking; cracks could prove serious if they allow intrusion of chlorides to the reinforcing steel. Costs of this method are uncertain primarily because they involve the consumption of liquid monomers far in excess of current production capacity. The ultimate cost may be comparable to present waterproof membranes.+

Another promising modification of concrete is the incorporation of small pieces of wax in the mix as it is poured. After the concrete has cured, heat is applied, melting the wax and sealing the cappillaries. Initially beeswax was used but because of greater availability and lower cost, montan wax, and later a mixture of parafin and montan wax, was used. In field tests to date, this treatment appears to produce a concrete that is impervious to attack by moisture and salt solutions.

Damage to the West Side Highway in New York City --

While it has been an accepted fact that deicing salts can cause serious damage to bridges and highway structures, and while there have been numerous reports and research on the matter, by far the most devastating damage that has occurred is the general deterioration of the West Side Highway in New York City (221,222,223,224). On December 15, 1973, the northbound roadway between Little West 12th Street and Gansewoort Street collapsed. (See Figure 9). At that time the Transportation Administration of New York closed the section of the highway between the Battery and 46th Street for an indefinite period. Immediately thereafter the Division of Bridge Design of the

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* Lehigh University is currently under contract to the Highway Research Board to investigate the feasibility of impregnating concrete to the depth of the reinforcing rods.

\+ According to Hay (225), polymer impregnated concrete contains by weight approximately 6% polymer, or about 3.6 kg of polymer per square meter of surface to the depth of 2 1/2 cm. Current costs of Lucite range from $.66 to $.88 per pound indicating a direct cost of monomer of $2.37 to $3.27 per square meter. The remaining costs would be attributable to heating and labor.

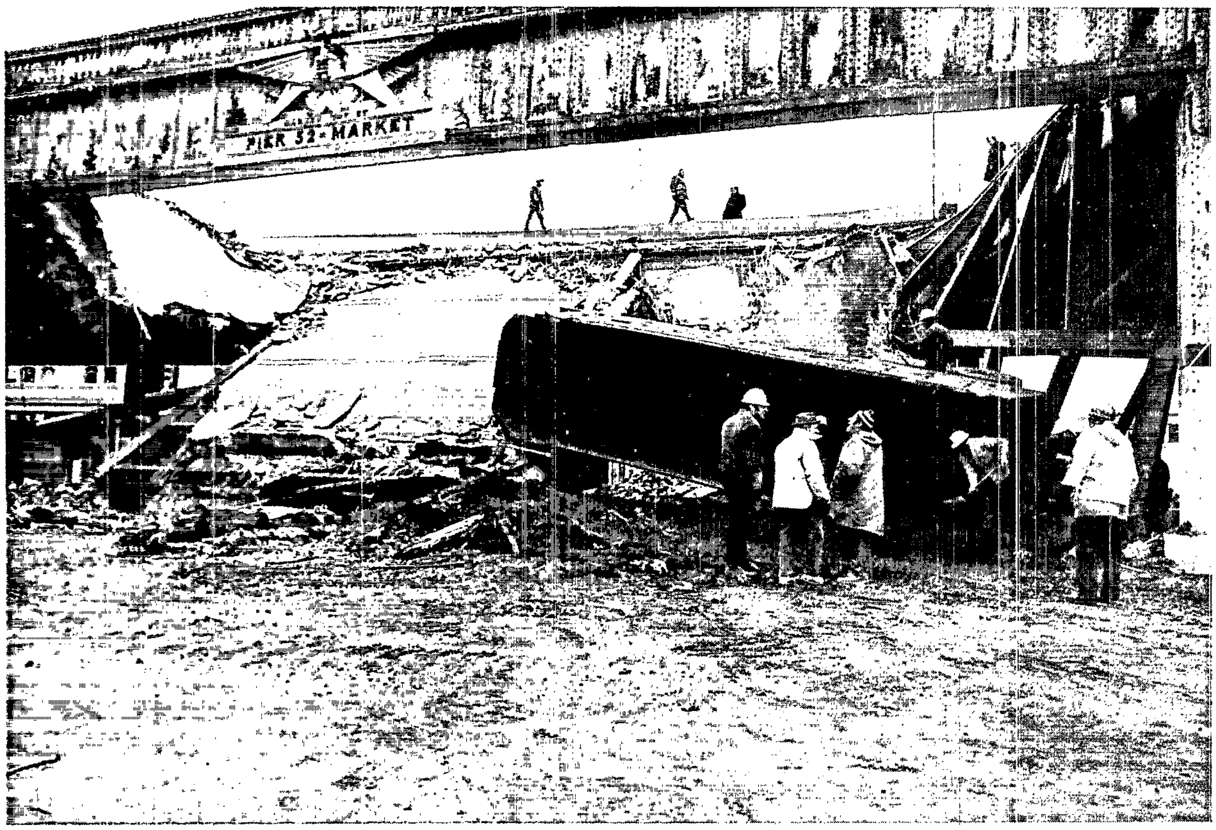

Figure 9. Collapse of West Side Highway at Ganesvoort Street on 12/15/73
(*New York Times* Photograph)

Department of Highways performed a preliminary survey between the Battery and 59th Street and confirmed the extreme structural deterioration of the connections between longitudinal girders and transverse floorbeams. (See Figure 10).

There had been no inspection of this city-built highway for 40 years. Following the 1967 collapse of the Siver Bridge in West Virginia, from I-Bar failure related to stress, National Bridge Inspection Standards

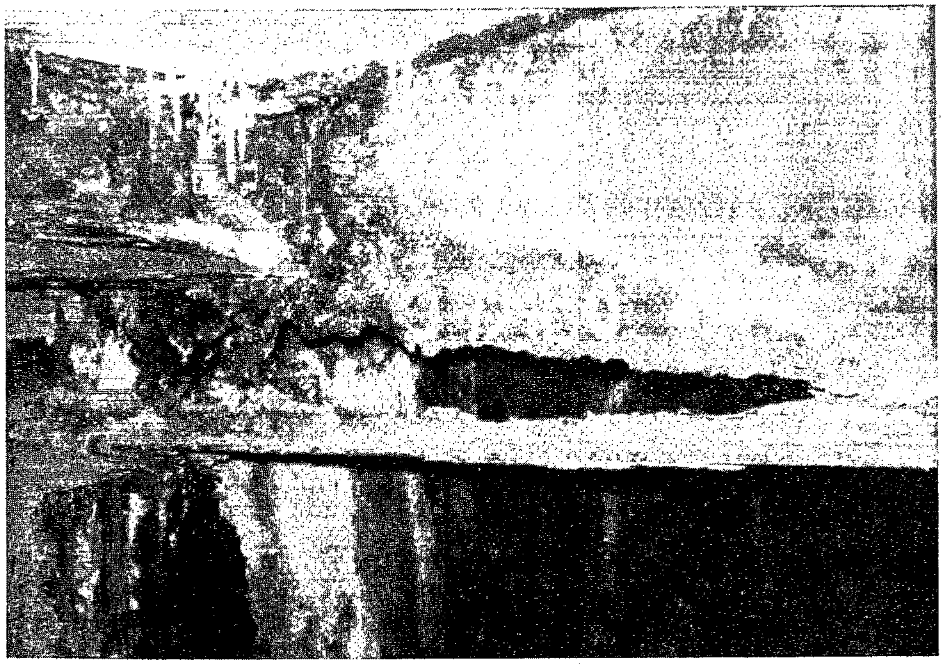

Figure 10. Typical Stringer Web Deterioration on West Side Highway Structure
(Photograph courtesy of Department of Highways, New York City)

were instituted in 1968. For the city to determine the true condition of the West Side Highway, however, the Transportation Administration contracted Hardesty and Hanover, Consulting Engineers, to conduct a complete examination. Their analysis, conducted from July 9 to November 14, 1974, resulted in four substantive volumes, the last dated May 30, 1975. The following quotes are taken in context from the most recent report:

> "The deterioration of the West Side Highway has been a continuous problem. As early as the mid-fifties public officials had anticipated its early demise. The use of salt to remove ice, combined with heavy traffic, has caused disintegration of large sections of the roadway. On several occasions, prior to the December 15, 1973 failure and closing, portions of the roadway slab have fallen into West Street. The asphalt overlays, which replaced the original granite block wearing course, are also in poor condition with holes and surface cracking. The damaged concrete has been temporarily repaired by covering the holes with steel plates supported by the steel superstructures which, in certain areas, has been subjected to extensive corrosion." (224, p. 21)

> "Our inspection between the Brooklyn Battery Tunnel and midtown reveal that serious conditions and deterioration exist at many locations on the West Side Highway; therefore, the entire roadway south of 46th Street should remain closed until a decision is made whether to demolish the structure or to proceed with repair and rehabilitation."

"The deterioration is a direct result of water and waterborne salt leaking through the expansion joints and the concrete deck. Water passing through the wearing course follows the slope of the concrete deck to the longitudinal girders where it leaks through cracks or through the joint between the deck and the girder web. Depending on the cross slope either the exterior or the interior floorbeams are affected." (224, p. 25)

The report concludes that although restoration of the highway is feasible, the cost of the work is almost prohibitive. The chief engineer* for the New York City Department of Highways estimates that it will cost $58 million to perform a partial rehabilitation of the West Side Highway from the Battery to 72nd Street. Hardesty and Hanover suggest that restricted rehabilitation for maintenance of the existing structure including "new deck, median barrier, lighting, painting, and steel repairs would cost about $66 million in 1976." (224) A complete rehabilitation including some updating or modernizing would entail $88 million according to a New York City Highway Department representative. The fourth and most expensive serious alternative presently before the city council is a proposal to demolish the existing elevated highway and build a new interstate highway to be called the Westway.

Not surprisingly, the consultants conclude, in part, "Use of salt for deicing should be minimized. Other methods and materials for maintaining traffic during ice and snow conditions should be considered." (224, p. 35) The chief engineer* affirms that deterioration of the West Side Highway structure was accelerated by the brine of dissolved rock salts compounded by the problem of poor drainage.

While the cost of the repairs to the West Side Highway may not be representative of typical bridge damage, there are other examples of costly salt induced deterioration. Recently it was reported that four Washington, D. C. bridges had become dangerous to traffic because salt had caused extensive corrosion of the reinforcing steel. The cost of the repairs is $11.7 million. (330)

Pavements --

With proper attention to design, materials and construction, cracking can largely be controlled. Concrete pavements are less vulnerable to spalling than are bridge deck pavements due to a number of factors: (1) bridge decks are subject to greater flexing stresses; (2) reinforcing steel is not as common in highway construction but where it exists the concrete cover is generally twice as thick as the 2 inches normally used in bridge deck construction; (3) transit mix concrete, which is more variable because of the use of several mixers, is usually used to cast bridge decks; central mix concrete is normally used for highways; and (4) other factors including reduced homogeneity resulting

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* Personal Correspondence with the Chief Engineer, Division of Bridge Design, Department of Highways, New York City.

from extensive hand finishing, and increased surface exposure subjecting parts of the bridge structure to environmental stresses such as freeze-thaw action that the underside of pavements are protected from. For these reasons, salt related damage to highways is far less frequent than damage to bridge decks.

4.2.3 Utilities

There have been a number of reports of corrosion damage to underground water mains, telephone cables and electric lines (15,26) resulting from the use of deicing salts. There have also been reports of damage to above ground electrical insulators from airborne roadsalt (318). The evidence at the time of these reports did not clearly show that road salts were to blame. That link has now been clearly established by two very thorough analyses.

Telephone and Electric Power Transmission Lines--

The first study was carried out between February and June of 1974 under the direction of Joseph D. Block, Executive Vice President of Consolidated Edison Company of New York (246). Mr. Block took on the study in response to the statement that there is "little data available either to substantiate or to disprove these reports" of corrosion to underground power transmission lines in the 1972 report, Deicing Salts and the Environment produced by the Habitat School of Environment and the Massachusetts and National Audubon Society (26). On June 3, 1974, after extensive analysis of corrosion damage and salt use in all boroughs of New York City between 1970 and 1974, Mr. Block wrote the following to the Habitat School of Environment:

> "Con Edison operates in New York City the largest system of underground electric facilities in the world. We had a unique opportunity in the past two years to assess the damage to this system by reason of the use of salt on the City streets. The winter of 1972-73 was quite mild and there was very little snow. The City used only about 20,000 tons of salt during the winter and I suspect most of this was used on bridges and bridge approaches, etc., which are more apt to be subject to rain freezing on road surfaces than are average City streets.
>
> During the past winter there were two storms of serious proportions when the streets were heavily salted. One of these storms was in December, the other was in January. The City used approximately 120,000 tons of salt this past winter or 100,000 tons more than the winter before.
>
> The effect of this salt on our electrical system becomes evident almost immediately after it is used and continues for two to three months as thawing snow and rainstorms wash the resultant brine through our subway systems. Our secondary cables (generally rubber insulated and operating at 120 volts) develop short

circuits and catch fire. There were approximately 1,400 more manhole fires this past winter than the previous winter. These additional manhole fires required extensive repairs and the replacement of almost 1,000 sections of secondary cable at a cost in excess of $4,000,000.

The effect of the salt on our primary feeders (cables operating at 13,000 and 27,000 volts) develops more slowly because of the heavier insulation and better coverings than are used on secondary cables. For the first four months of 1974 we had 125 more failures on our primary feeders than we did during the corresponding period of 1973. Replacement of cable associated with these failures cost Con Edison approximately $250,000.

We know that the brine has corrosive action on our underground transformers, switches and other equipment. It also has, as mentioned in your report, a deleterious effect on the concrete in the manholes and ducts used in our subway systems. Because these effects do not become apparent for several years, we cannot place a price on the deterioration caused this past winter.

Altogether, it is safe to estimate that the salt spread on the streets of New York City resulted in additional expenditures by Con Edison in excess of $5,000,000 during the winter of 1973-74 (245)."

No estimate of the cost to consumers as a result of power outages has been made. Based on the data collected by Mr. Block, several hundred power outages during the severe winter months can be attributed to road salt use. The cost of such extensive power losses is very significant in terms of inconvenience, lost production time, and lost personal time.

It is likely that the costs incurred by Consolidated Edison are far larger than those incurred by any other municipal electric company. Very likely many other instances of electrical damage that have not been so well documented and analyzed will be found to be salt related. Mr. Block's analysis will hopefully pave the way for other large utility suppliers (and users) to document and to investigate their own reports of salt-related damage more thoroughly.

As explained at the beginning of Section 4, it has been shown that deicing salts enter into the atmosphere and are carried farther from the initial point of dispersal (highways) than occurs from splash and runoff. In general, air pollutants (participate and gaseous) can cause a variety of problems in the operation of electrical apparatus. The buildup of pollutant films on the contacts of electrical connectors hampers the flow of electrical current and thus impairs operation. Particulate matter deposited on the contacts can also prevent the connector from closing completely and again the current flow is impeded.

In a paper on the influence of air pollutants on electrical connectors, the economic importance of air pollutant problems is discussed (317). The paper points out that connector miniaturization was being limited by the difficulty in maintaining clean surfaces due to air pollution. In addition, any estimate of the economic losses due to air pollutants probably do not include the factor of expensive chemically resistant materials, such as gold, being required in place of cheaper materials which would not be as resistant to air pollutants.

A very serious problem in the transmission of electrical energy is the contaminant buildup on insulator surfaces. The problem is not unique to salt particles but sea salt is one of the most conspicuous offenders. One survey (318) specifically noted road salt as the cause of some power outages.

The reliable and uninterrupted operation of modern power systems depends on insulation which must not deteriorate or allow disturbances, flashovers, and/or line outages. The deterioration and flashovers that do occur are mainly the result of air-borne deposits from natural (sea salt), as well as man-made (generally industrial) sources including road salt.

The accumulation of pollutant layers on insulators is a complicated process depending on electrostatic, gravitational, and wind forces and influenced by insulator shapes, the surface conditions, corona discharge, and rainfall (319). Dry deposits usually do not lead to disturbances such as flashovers. Natural processes such as high relative humidity, fog, dew, frost, and rainfall cause the pollutant layer to become moist (especially when the deposits are hygroscopic as are salt layers). These moist layers were reported in 1966 to be the second major cause of line outages (320).

The processes leading to pollution flashover on electrical insulators are as follows. When the insulator surface becomes moist, current flows across the surface and the resistive heating leads to the formation of dry bands. Flashovers occur if one of the discharges across the dry bands propagates across the entire wet surface (320).

That electrical insulator contamination is a serious problem is evident from the rather large number of papers on the subject in the IEEE <u>Transactions on Power Apparatus and Systems</u>. An incomplete survey of the literature noted over 25 papers on the subject since 1969.

In 1971, the results of a survey of the problem of insulator contamination in the U.S. and Canada were published (318). A questionnaire had been sent to 90 utilities and 59 responded with 309 case histories of transmission line outages. Each case may contain a great number of flashovers on different insulators and numerous outages. Determination of cause was made by the utility company engineers. Road salt was most often a source of outage in fog conditions. Although this survey found only 20 of the 473 outages were attributed to road salt, from other information gathered since 1971 it is likely that the true extent of salt as a causative factor has been understated. Since deicing salts appear to be widely dispersed throughout northern U.S. urban areas in the winter and spring months, it appears that there are a number of variables (proximity of power lines along high speed highway, amount of salt used, type of insulator, etc.) that make power failures caused by deicing salts more common in certain areas. The resulting frequency of outages in a few areas means an even higher cost of inconvenience to the users affected.

Underground Pipe Corrosion --

Soil moisture is a necessary condition for the external corrosion of gas and water mains to occur. The corrosion process is enhanced by a number of additional factors, one of which is the presence of sodium and chloride ions from dissolved deicing salts. Natural soil resistance to electrolyte migration is decreased by salt in solution. The electromagnetic corrosion process discussed in Section 4.2.1 is similar in the case of underground pipe corrosion. Decreased electrical resistance of the soil allows the electromagnetic field set up between anode and cathode to expand, and thus charged ions can travel greater distances through the soil and the corrosion rate increases. (245)

Summary --

The continued use of chloride salts in winter months will affect utility companies' equipment, through direct corrosion where brine contacts metal and concrete surfaces and through changes in electrical insulation caused by airborne particulate salt debris. When these damages are allowed to continue unabated, we will find ourselves absorbing social costs in inconvenience, interruption of service, exposure to increased chances of electrical fire or gas or water main leakages, in addition to more out of pocket costs as the utilities pass on repair costs to the consumer. These costs are more fully detailed in Section 5.

4.2.4 Industrial Production

The impact of sodium chloride in water used for industrial production has received mention in the literature. The maximum allowable levels of chlorides for some of those industries are as follows: Carbonated beverages, food equipment washing and paper manufacturing (Kraft) - 200 to 250 mg/l; steel manufacturing - 175 mg/l; textiles, brewing and paper manufacturing (soda and sulfate pulp) - 60 to 100 mg/l; dairy processing, photography and sugar production - 20 to 30 mg/l (15). However, there is little mention in the literature of actual cases in which there were costs incurred by industries because of concentrations above these levels. One industrial user in Peoria, Illinois was forced to switch to city water because of salt contamination of its private well (126).

SECTION 5

THE COST OF SALT-RELATED DAMAGE

5.1 METHODOLOGY

The evidence summarized in the preceding section suggests strongly that deicing salts may and do cause damages that frequently are not taken into consideration by those responsible for winter highway maintenance. Part of the problem lies in the fact that -- while the possibility of these damages is generally known -- their likely extent and incidence are only vaguely perceived. In order to improve the decision making process relating to the intensity and pattern of salt application, it is necessary to provide policymakers with the means to evaluate the total costs of salt use. Unfortunately, most of the research that has been conducted on the potential damages of deicing salts has been more of a case study nature. This orientation has led to a situation in which research findings are interesting, but often irrelevant to or useless for decision making, at the local or state level.

The present study examines the available evidence for its potential to yield some indication of the likely total costs of salt use. It is clear that there is a critical constraint: the basic orientation of past research. It is difficult, if not impossible, to infuse decision relevance into research that was never intended to be designed to yield information for policymakers. The method in this study has been to clarify prior constraints, to approach the problem of cost determination and estimation from a comprehensive framework, to assess the usefulness of available research against this framework, and finally to use the (often extremely sparse) empirical evidence to derive some indicators of the potential range or approximate order of magnitude of costs for various damage categories.

Figure 11 sketches the broad framework describing the ways in which the application of road salts generates direct and indirect costs to individuals and society. Basically, direct costs are required expenditures by either individuals or government as a representative of society; indirect costs denote losses in welfare which may affect members of society individually or collectively. The application of deicing salts introduces into the environment a foreign substance which changes characteristics of natural or man-made resources directly or indirectly (by affecting the environmental conditions determining their survival or life expectancy) in a way that reduces their usefulness. These reductions in usefulness can be related, at least at a conceptual level, to dollar costs which

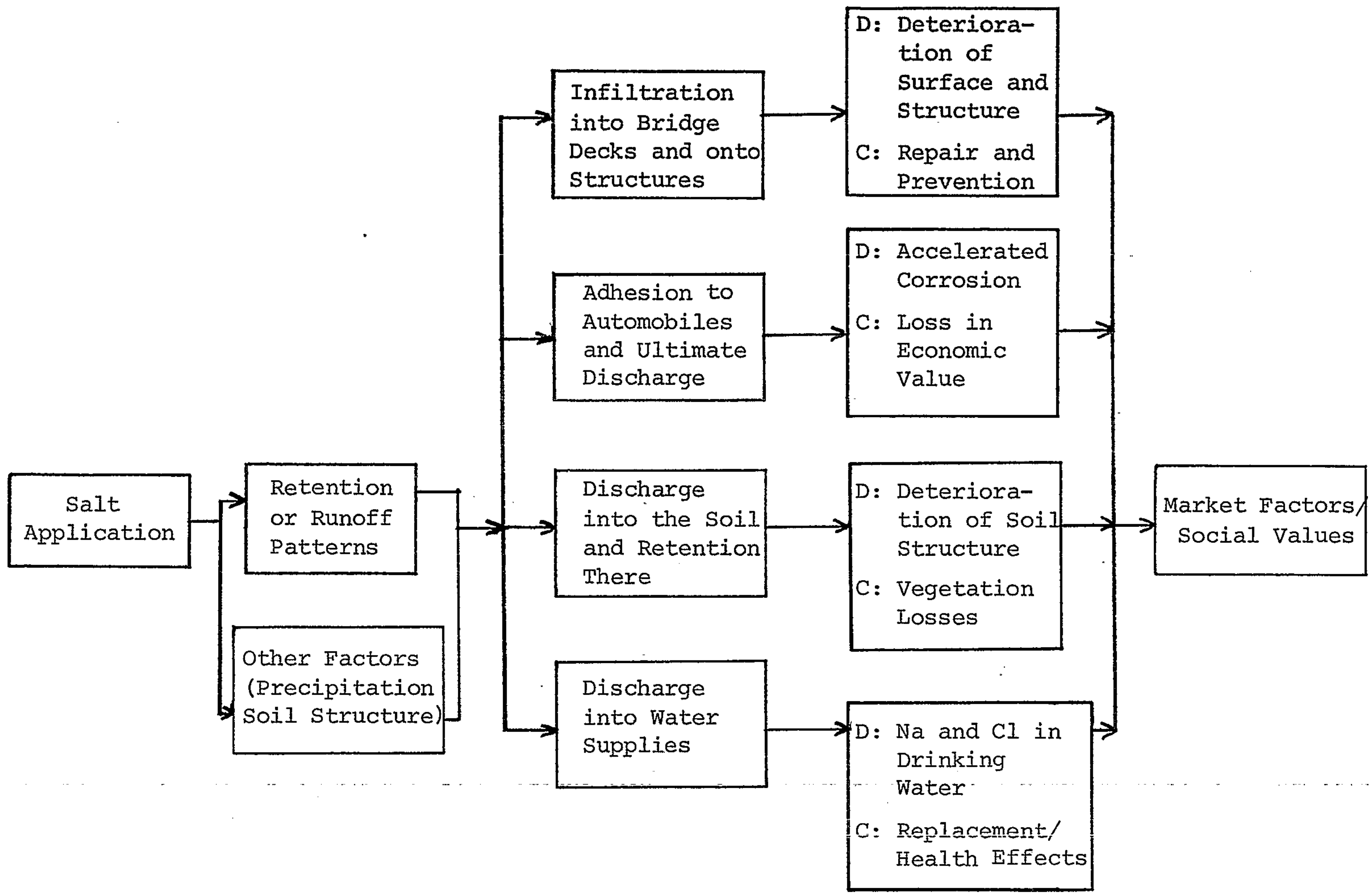

Figure 11. Schematic Overview of Cost Generation Framework
D represents Damages; C, costs.

describe the damages in terms of a common denominator. These costs (estimated or imputed) are an expression of the value of the "lost usefulness" of the respective resource, or the cost of restoring that resource to its full usefulness.

The main problem in the application of this framework to the actual estimation of costs is the nature of the relationships between damages and salt application. The damages resulting from the introduction of salt into the environment are the result of complex processes. Generally, numerous factors other than salt must be taken into consideration in analyzing the relationships between salt use and any suspected damages. Present knowledge of the interaction of these factors is limited. In addition, the processes also depend on the timing of certain phenomena. For example, in many instances, the damages associated with salt brine runoff from the highways to vegetation or water supplies depend on precipitation patterns. Since precipitation fluctuates randomly over the year, it is entirely possible that the same amount of salt applied in two winters produces completely different effects as the result of differences in precipitation patterns, all other things being the same. Moreover, the amounts of salt applied tend to vary considerably over time in response to differences in the incidence of snow and ice on highways. All of these elements interact to produce considerable uncertaintly in the known relationships between damages and salt application. This uncertainty impedes the development of a micro-analytical model which translates the relationships shown in Figure 11 into functional and quantifiable expressions.

Part of this problem could be overcome by treating the uncertainty in the functional relationships between deicing salt use and associated damages through a probabilistic approach. This approach can be sketched schematically in a form of the following expression:

Cost = Probability of Damage per Unit of Resource Exposed X
Population (Number of Units of that Resource) at Risk X
Cost per Unit of Damage

The resource in question may be water supplies, automobiles, underground cables, or any of the other elements that have been identified as being adversely affected by deicing salts.

The formal presentation of the probabilistic approach to deal with uncertainties identifies the data required for its implementation. The most important data element is the determination of the probability of damage for a given resource exposed to the effects of deicing salts. The estimation of these probabilities requires a considerable amount of data, which allow for the isolation of the net effects of deicing salts either under controlled conditions, or through multivariate analysis which can account for other relevant factors. In a controlled situation, experimental data have to be sufficient to describe some form of dosage-response relationship, while non-experimental data have to be obtained through such methods as epidemiological studies. For generalization, the latter requires a sufficient sample of the population at risk (which may be quite small, depending on the problem). The non-experimental approach therefore implies that population-at-risk figures are already available for the selection of the sample used in estimating the damage probabilities.

Data on the population at risk are needed regardless of the way in which damage probabilities were derived to estimate the total (expected) incidence of damages. This figure can then be multiplied by some equivalent of the cost per unit of damage.

The data requirements and analytical steps can best be illustrated by means of an example. In order to compute the costs of salt-related damages to roadside vegetation, primarily trees, the probability of damage could be defined as the probability of death for a given amount of sodium accumulation in the soil. (Assume for simplicity that death is the only relevant damage category, which abstracts from a more continuous spectrum of damages). For different kinds of trees, these probabilities may have been established through controlled experiments. Available studies on sodium concentrations in soils at different distances from the highways that can be attributed to deicing salts could then be used to define and enumerate the population at risk (e.g., all trees within a 9 meter band along "bare-pavement" highways.) Multiplying the probability of death by the number of trees exposed to the risk would then yield the expected number of tree deaths attributable to the use of deicing salts. Unit costs per dead tree, finally, could be derived from available estimates of the value of shade trees.

In this particular example, the only information item that is available -- although with certain qualifications -- is the unit cost. Actual experiments, for example those reported in "Salt Damage to Trees and Shrubs" (168), have tended to yield less than conclusive evidence on the damage probabilities. However, more important is the absence of data (any data) on the population at risk. Trees along highways that are candidates for deicing salt application simply have not been counted. Similar data gaps exist with respect to other natural or man-made resources that are affected by salt-related damages.

In the absence of any data required to implement a more comprehensive approach, ad hoc methods have been used to take advantage of certain pieces of information that give some impression of the magnitude of the problem. This step had to be taken in a number of damage categories discussed below.

The analysis comes closest to the ideal approach with respect to damages to automobiles, where multivariate analysis is used to determine the incidence of salt-related damage, motor vehicle registrations provide reliable data on the total population at risk, and car prices can be used to determine the unit cost of salt-related damage. It is interesting to note that this method yielded the highest cost estimate of all categories examined.

5.2 COSTS OF WATER SUPPLY CONTAMINATION

Water supplies have been and continue to be contaminated by the runoff of deicing salts from highways. The degree to which salt applied to the road surface infiltrates water supplies in the form of sodium and chloride ions may vary in response to factors such as soil consistency, distance, topography and climatic conditions.* But the evidence summarized in Section 4.1.1 is sufficient to demonstrate that the use of deicing salts has led to serious problems in assuring the supply of high-quality water in many portions of the snowbelt region. The present section complements this summary of the technical evidence by examining the magnitude of damages to water supplies, primarily drinking water, in economic and social terms.

The evaluation of the total social costs of water contamination as a result of deicing salts faces a number of conceptual and empirical obstacles. The very nature of the costs incurred by government and individuals as a result of salt contamination of drinking water supplies hampers their enumeration and evaluation. In contrast to damages to physical structures, such as highway bridge decks or automobiles, which require scarce resources for any remedial action, it is possible that the contamination of water supplies may be mitigated as a consequence of natural processes (such as precipitation). Empirical data show considerable fluctuations of sodium and chloride levels around critical values. + These fluctuations exhibit a random pattern. The occurrence of acute contamination problems (sodium or chloride concentrations exceeding some criterion level) therefore can be predicted only as a probable event. This problem can be illustrated by Figure 12 which shows chloride concentrations in surface waters in Rhode Island (291). If 60 mg/l are regarded as a critical level ‡ a (crude) probability estimate for the East Providence case to exceed this level in any given year would be 40%, since the threshold was crossed twice in five years. In addition to the occurrence, the extent of contamination and its duration are also subject to random factors.

These characteristics influence the behavior of any direct or indirect costs over time. Since these costs arise in response to the occurrence and extent of any contamination, neither their occurrence nor their

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* The discussion here focuses on groundwater contamination, since runoff into surface water constitutes different problems, at least in standing water bodies. In flowing surface water, salt concentrations rarely reach significant levels.

\+ These random fluctuations occur against a steady, and often accelerated upward trend in the sodium and chloride levels of drinking water supplies.

‡ The chloride level at which the sodium content exceeds 20 mg/l with near certainty

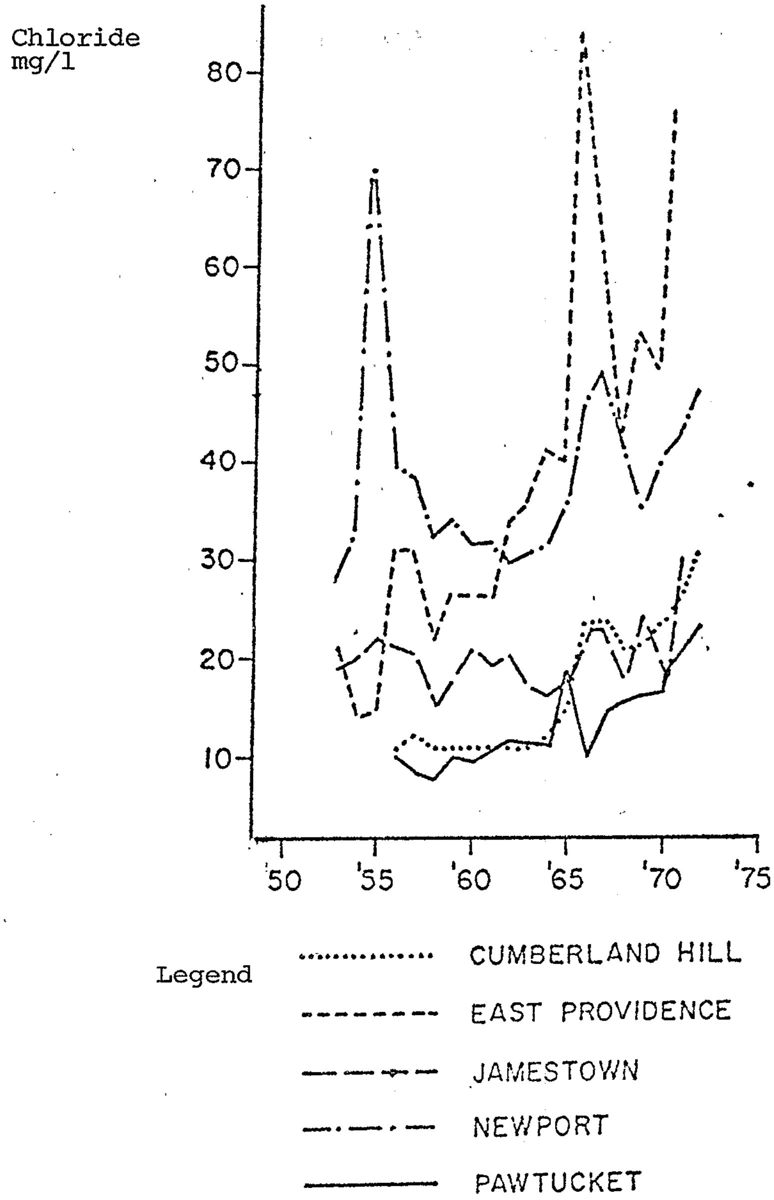

Figure 12. Rhode Island - Surface Waters
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magnitude follow a regular pattern over time. This feature hampers the development of a micro-analytical cost model for water supply contamination.

The conceptual issues are compounded by problems of data availability. Neither the direct nor the indirect costs of excessive levels of sodium and chloride in drinking water have been measured in a comprehensive manner at any level of aggregation. For example, even simple cost items (such as the costs of more frequent testing once chloride levels are approaching threshold levels) cannot be culled from existing expenditure records, since accounting procedures at the local or state level tend to lump these costs with expenditures on routine activities. The empirical evidence required for the cost analysis at the necessary level of detail thus often simply does not exist.

Finally, apart from the problem of the appropriate conceptual framework and data availability, the analysis also has to cope with a serious issue of a more philosophical nature. Probably the most important indirect cost of salt contamination of drinking water supplies is related to the health effects of increased sodium intake by users. High levels of sodium intake have been found to contribute significantly to increased morbidity and shortened life expenctancies (e.g., in 134). The evaluation of such effects in economic terms faces a number of issues that have been debated in health economics for some time. While several methods have been developed to "cost out" the detrimental effects of some substance or factor on public health, none of these techniques resolves the basic philosophical dilemma -- placing a dollar value on human life. Generally, the costs of ill health can be measured by including direct expenditures on diagnosis and treatment, as well as the opportunity costs of losses in productive activity, i.e., the value added foregone by society. While this approach is useful in a purely economic context, it has the serious drawback that the ill health of "non-productive" members of society (persons outside the labor force) cannot be directly evaluated in this manner. The analysis below therefore provides only estimates of the likely ranges of health effects, without attempting to translate them into dollar figures.

Given the problems of conceptual complexity and of observation and measurement for estimating the costs of salt contamination of drinking water supplies, the approach taken here focuses on the development of a comprehensive framework designed to cover all direct and indirect cost elements on a per capita basis. The cost model is subsequently used to explore the range of likely total costs on the basis of available information and reasonable assumptions about specific unit costs. This discussion is followed by an assessment of the principal health effects associated with increased sodium levels in drinking water supplies.

5.2.1 Cost Estimate Framework

As noted in Section 5.1, several dimensions of the cost analysis can be distinguished. For the costs resulting from the chloride and sodium contamination of drinking water supplies, the general breakdown can be illustrated by means of selected examples shown in Table 1. This breakdown distinguishes direct and indirect costs. Direct costs involve expenditures or use of resources to remedy any damages related to salt contamination. Indirect costs can be viewed as damages to individuals or society as a whole that involve a reduction in the level of welfare of the party or parties concerned without requiring any direct outlays.

Table 1

Dimensions of Costs Associated with Salt Contamination of Drinking Water

(with Sample Cost Items)

Cost Type	Cost Incidence	
	Individuals	Society
Direct	Cost of replacement of private wells as a result of the contamination of existing wells.	Cost of installation of special drainage ditches and catch basins to keep salt runoff from water supplies.
Indirect	Losses in private property value in areas exposed to the risk of drinking water contamination through deicing salts.	Losses in value added as a result of the reduced productive capacity of individuals with a hypertension condition exacerbated by sodium in drinking water.*

* Largely a cost to society, since individuals are at least partially compensated through some form of transfer-payment.

In terms of the incidence of costs, two major groups can be distinguished: government (at all levels) as a representative of society as a whole, and individual members of society. Although this distinction is somewhat arbitrary, it is useful by allowing for a more detailed breakdown of the types of costs incurred as a result of the contamination of drinking water supplies. In addition to contributing to a more structured analysis, the distinction also allows for an assessment of the equity implications of alternative institutional arrangements. One example may illustrate this point. As a consequence of the application of deicing salts, private wells have become contaminated in several states. In most areas, it is the primary responsibility of the individual well owner to finance measures necessary to cope with this problem, at least in the shortrun.* In a few instances this problem has been reflected in losses in property value that can be directly attributed to the salt problem. The incidence of costs can be shifted from affected individuals to society. There is at least one instance in which the state has accepted the responsibility for any costs related to the contamination of private wells through deicing salts. New Hampshire instituted a well replacement program as far back as 1956, with the state paying for the replacement of wells that have been determined to be contaminated by salt runoff from highways (265). While this program does not imply a complete shift of the cost burden from the individual to society as a whole (there is a substantial waiting period involved, partially because of the large volume of claims), it may result in a more equitable distribution of the net costs (or net benefits) of the use of deicing salts. The discussion will return to an examination of the equity aspects below.

The examples shown in Table 1 suggest some of the difficulties of delineation of cost categories. Particularly in the area of direct vs. indirect costs, a general line cannot be drawn. Too much depends on the particular arrangements and the extent to which water contamination may go unnoticed. The discussion below therefore focuses on the cost implications of remedial measures that restore affected water supplies to their original quality (e.g., through well replacement). The analysis of indirect costs focuses on health effects only.

Direct Costs --

The identification of the relevant direct costs to either society or individuals calls for a look at the process which gives rise to these costs. Since the contamination of drinking water supplies is

* There are of course several possibilities in the longer term to shift any costs to society, for example, by lobbying successfully for any form of compensation, or for the construction of special drainage ditches that will prevent salt runoff into private wells.

primarily a public health problem, analogies from medical care can be used to structure the cost-generating process. The direct costs incurred by either water supply agencies or users of public or private water supplies can be grouped into three broad categories: the costs of prevention, of diagnosis and of treatment.

Prevention: The growing awareness of the potential impact of the use of deicing salts on the contamination of public or private water supplies with chlorides and sodium has led to an increased emphasis on preventive measures. These measures include the installation of special drainage ditches and catch basins for salt brine runoff from highways, the selection of well locations at a sufficient distance from highway drainage areas, the incorporation of water supply locations in highway route planning, and any other measures designed to lower the chances of infiltration of salt brine runoff into private or public water supplies.

Diagnosis: Practically all public drinking water supplies are monitored on a periodic basis with respect to a variety of constituents. As a result of the accumulating evidence concerning sodium and chloride contamination, these monitoring activities have been stepped up in a number of instances. For example, the State of Massachusetts traditionally had limited its tests to the determination of chloride levels (together with a variety of other substances). Recent concerns over the salt contamination of drinking water supplies have led to the introduction of sodium tests as part of the regular monitoring procedure in 1970 (see 53). Diagnostic costs also include outlays for studies designed to identify the source(s) of observed contamination problems, assess their implications for the future, and determine appropriate remedial steps. Finally, the category of diagnostic costs also covers all incremental expenditures incurred in handling user complaints and inquiries and in following up on specific cases. Such costs apply, for example, to the U.S. Environmental Protection Agency's mandate to participate in the supervision of drinking water quality.

Treatment: Once a serious contamination problem has been identified, persons responsible for a given water source (either public or private) have to take some form of remedial action. The definition of a "serious contamination problem" may vary across the snowbelt region. In terms of chloride, most states and local water supply agencies focus on the recommended limit established in 1962 by the Public Health Service at 250 mg/l. However, in several instances, levels considerably below this limit have been taken as a cause for action. Particularly with the increasing concern over the sodium content of drinking water supplies, chloride levels as low as 30-70 mg/l may be cause for concern*.

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* While the relationship between sodium and chloride contamination varies in response to soil consistency and precipitation patterns, a rough guideline is a ratio of 2:3 to 1:3. A chloride level corresponding to a sodium concentration of over 20 mg/l may therefore be cause for concern.

Remedial action or treatment may assume several forms. It may range from modifications of the current water supply system and its environment to a complete replacement of the water source bv some alternative. Modifications of the current system include, for example, attempts to reduce the chloride or sodium concentration by "flushing" the well, changes in drainage system for the area (which may involve the installation of special drainage ditches or the implementation of any of the other measures discussed under prevention), or reduction of production from the affected well(s) in the hope that sufficient dilution will occur. Such measures are likely as long as the observed concentrations do not yet pose a public health problem.

Once the concentrations approach or exceed the critical level -- generally defined in terms of the recommended chloride limit of 250 mg/l -- the principal course of action followed by public water supply officials or users is the switch to other water sources. The cost implications of such a course of action vary considerably with the characteristicss of the system. For example, a town that is dependent on one main well may have to purchase water from other sources at substantial additional cost, or may have to invest in the development of a new well. In contrast, a town employing a number of wells may just have to increase production from non-affected wells to replace a well that had to be closed because of chloride contamination. For private water supplies affected by salt runoff, the only alternative is generally the drilling of a new well, preferably at a sufficient distance from the highway drainage area. Several studies have indicated that a minimum distance of approximately 15 meters from the highway shoulder is necessary to reduce the likelihood of deicing salt contamination of private water supplies, e.g., (95), on some lots such as relocation may be difficult, because of the location of the septic system.

Another possibly major cost element is the reaction of users to current sodium levels in drinking water. Persons on a low-sodium diet for medical reasons may become concerned over the possibility of excess sodium in their drinking water, preferring instead to purchase bottled water (which may or may not be "pure"). Without a specific survey, it is impossible to predict what percentage of the population follows such a course of action. Here again, it is important to remember that sodium concentrations vary randomly as a result of natural factors or because of variations in the amounts of salt applied. Since it is virtually impossible for the individual user to test the drinking water himself, his or her decision as to the use of tap vs. bottled water generally is based on haphazard information from the media, or responses to inquiries to water-supply agencies. This information base tends to leave a substantial uncertainty. Given the potentially high risk for individuals with a hypertension condition, the best course of action may be to purchase bottled water.* The likely costs of these purchases must be included under the treatment category.

These considerations establish a basis for listing the major direct cost items associated with the contamination of drinking water supplies by deicing salts. Table 2 presents a fairly comprehensive list of these cost items, together with an assessment of the relative magnitude of the costs and the likelihood of their occurrence. The assessments of magnitude and occurrence are based on the evaluation of the relevant literature. As noted above, no comprehensive data base exists that would allow for a complete enumeration of cost elements and their likelihood of occurrence. The analysis therefore must be based to some extent on best judgment.

The distinction of magnitude and likelihood of occurrence is necessary to obtain a representative estimate of total social costs. The discussion above has mentioned that the degree of water contamination varies over time in response to a variety of environmental factors. The process which causes direct costs (as well as indirect costs) therefore is a <u>random process</u>. Since complete data on the behavior of these processes in the past are not available, the total direct costs cannot be evaluated directly. Any cost estimate therefore becomes an <u>expected cost</u> -- the product of the actual costs and their probability of being incurred.

This point deserves additional emphasis. The direct (and indirect) costs associated with the actual contamination of drinking water supplies vary as a result of two factors. First, the physical processes leading to contamination levels are strongly subject to random variations in the occurrence and strength of important factors involved. Secondly, for the same level of contamination, any direct cost may vary considerably over time and across regions and towns as a consequence of differences in reaction on the part of those responsible, and in relation to differences in environmental and economic conditions. Since action alternatives to municipal and state officials are generally delineated in terms of budgetary constraints, actual direct costs may be higher in more affluent towns or states. While these differences are at least partially offset by differences in indirect costs, economic factors may produce substantial variations in the type of response and the associated costs. Under these conditions, representative expected costs constitute the principal option for the analysis.

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* A Massachusetts highway official acknowledged that this may be the best alternative to hypertensives by suggesting, perhaps somewhat cynically, that the state would still be better off by continuing its current salting policy and supplying hypertensive individuals with bottled water. (Quoted in the <u>Boston Globe</u>.)

Table 2

Direct Costs Associated with Salt Contamination of Drinking Water Supplies

Cost Factor	Relative Magnitude of Costs	Likelihood of Occurrence	Incurred by
Prevention			
Installation of drainage ditches along highways	Medium	High for "bare pavement" highways	Society
Location of new private wells beyond 12 meter strip along salted highways	Generally low	Low, only for new developments	Individuals
Maintaining a sufficient distance from water supplies in new highway routing	Generally low, but may add signicantly to costs	Low, only for new construction	Society
Reduction of the salt/sand ratio used in application	Extremely low, probably negative (i.e., savings)	High, likely to be included in all winter highway maintenance	Society
Improved monitoring of likely salt needs and actual salt use by individual spreader trucks	Nominal	High, likely to be included in all winter highway maintenance	Society
Purchase of land around public water supplies	Medium-High	Medium	Society
Diagnosis			
Increased monitoring and testing of water supplies	Low	High	Predominantly Society

Table 2 (Continued)

Direct Costs Associated with Salt Contamination of Drinking Water Supplies

Cost Factor	Relative Magnitude of Costs	Likelihood of Occurrence	Incurred by
Studies to determine causes of observed contamination and identify appropriate treatment	High	Low, but increasing	Predominantly Society
Studies/tests to ascertain role of deicing salts in contamination of private wells	Low to medium	Low, but increasing	Predominantly Individuals
Handling of complaints and inquiries concerning sodium chloride contamination of public water supplies	Nominal per case	Medium, Increasing	Society
<u>Treatment</u>			
Replacement of contaminated private wells	High	Low to medium	Generally individual but may be society (N. H.)
Purchase of water from other sources	Medium	Low	Individual and Society
"Flushing" of contaminated wells	Medium	Low	Society
Installation of protective devices (drainage ditches, catch basins)	Medium	Low	Society
Replacement of contaminated public wells	High	Very low thus far	Society

Indirect Costs --

Principally, all indirect costs associated with the contamination of drinking water supplies through deicing salts relate to the health effects. While it may be possible that water users experience a loss in welfare as a result of bad-tasting water, the costs of chloride contamination (below the threshold level of 250 mg/l established by the Public Health Service standards) are primarily in the nature of direct costs. The discussion here therefore deals primarily with the potential health effects of comparatively high levels of sodium in the drinking water. Because of the role of this public health hazard, the analysis focuses on health hazards related to hypertension (high blood pressure).

The evaluation of the indirect costs related to these health effects is difficult, since they can assume different forms. The discussion of direct costs above already indicates that such indirect costs can be converted into direct expenditures, if the individual concerned decides to forego public (or private) water supplies as a source of drinking water and purchases bottled water instead. In other cases, the risk of any adverse health effects associated with the drinking water quality in a particular town may result in direct economic losses in terms of property values.

The problem of indirect cost evaluation is further complicated by the role of ignorance and uncertainty in determining the actual health effects. Under conditions of perfect information, the opportunity cost of sodium contamination in drinking water supplies would be the cost of supplying individually approximately 20% of the population who are or should be on a low-sodium diet with "pure" water for drinking purposes, e.g., in the form of bottled water. However, since this option has been rarely exercised, the appropriate cost measure refers to the likely health effects of higher sodium levels in drinking water supplies which are in fact consumed. Based on these considerations, the exploration of the empirical dimensions of the problem below focuses on the likely health effects actually caused by the salt contamination of drinking water.

5.2.2 Review of the Empirical Evidence

As noted above, no effort has been undertaken to measure direct or indirect costs of the salt contamination of drinking water supplies in any comprehensive form at any level of aggregation. The thorough review of published and unpublished literature as well as the survey of operating agencies conducted as part of this study yielded very little useful information that would allow for an estimation of direct or indirect costs for more than specific instances. The approach here therefore reviews briefly the relevant information that has been obtained, and uses this information to derive some broad indicators of costs on a per capita basis, which can then be used to delineate the range of total costs associated with the contamination of drinking water supplies.

Direct Costs --

Probably the best data base for an evaluation of the likely range of direct costs is available for New Hampshire. The State of New Hampshire has shown considerable concern with the effects of highway salting policies on the environment, particularly water supplies. This concern has led to the institution of a well replacement program as early as 1956 (265). The program operates on a complaint basis only. The wells affected must be located near state-maintained roads. Well inspectors observe a well which has been contaminated for a year to determine whether the contamination (chloride level) is significant over a three to four month period. In order to quality for the replacement program, chloride levels must be around the 1962 PHS recommendation of 250 mg/1. However in practice a number of considerations are involved in determining whether a well should be replaced. Corrective action generally requires about a year to 18 months. The state will replace the well and the pump, once it has been established that the well is in fact contaminated as a result of state salt runoff from highways.

Budgeted for this program is an amount of $200,000 per year (up from $100,000 prior to 1973) for the well replacement itself. In 1974, 50 wells were replaced at a total cost for labor and materials of $132,000. Table 3 shows the number of wells replaced since 1965 and the associated total costs and costs per well. There is no evidence for any trend in the figures, except for a long-term increase in the cost per well, (although these costs have declined over the last three years), which is attributable to inflationary patterns. Aside from this trend, cost per well varies considerably over the years. These variations tend to reflect variations in construction conditions. For example, additional costs are incurred, if deeper wells have to be drilled or more elaborate pumps (other than simple jet type pumps) have to be installed.

The costs shown in Table 3 only refer to the direct costs of well replacement. In addition, the Special Services Division of the New Hampshire Department of Public Works responsible for the well replacement program maintains a payroll of about $80,000 (1974). The actual costs of operating the program also include maintenance and depreciation for five cars, the costs of approximately 200 water samples annually, and any costs incurred as the result of drainage corrections requested by the Division and implemented elsewhere. (265)

All these costs taken together amount to approximately $0.25 per capita per year. Since the well replacement program only refers to wells contaminated by state salt, the actual required costs for maintaining an adequate water supply in New Hampshire are higher. Given that state salt amounted in 1972 to approximately 24.5 percent of the total for the state, the total direct costs associated with deicing salts in New Hampshire may amount to $1.00 per person, or $700,000 for the state as a whole. While this figure appears very high, it should be kept in mind that it would constitute a catch-all figure for all the direct costs that would be

Table 3

Costs of New Hampshire Well Replacement Program

Year	Number of Wells Replaced	Costs (in thousands)	Costs per Well
1965	44	$ 80.3	$ 1,825
1966	53	128.4	2,421
1967	62	109.4	1,765
1968	42	85.6	2,038
1969	40	97.8	2,329
1970	38	85.6	2,253
1971	17	41.9	2,465
1972	30	93.9	3,130
1973	27	77.5	2,870
1974	50	132.0	2,640

involved in restoring a water supply system to a state characterized by tolerable levels of chloride contamination. In this sense, it can be regarded as a total expended cost figure.

Extrapolation of this figure to the U.S. as a whole is difficult. It would be misleading to use the per capita cost figure for New Hampshire as indicative for all other states. At a minimum, two factors must be taken into account: salting intensity (total salt per lane mile) and the relative importance of wells, which are much more susceptible to salt contamination than reservoirs, as sources of the population's water supply. Using only salting intensity by state as a weighting factor for extrapolation, the New Hampshire per capita costs to the nation yields a total cost estimate of $46.5 million per year. Since New Hampshire tends to rely on groundwater as sources of water supply at a slightly lower rate than the nation as a whole (20% vs. 21%), the potential cost of replacing contaminated wells would be slightly higher. However, the available evidence, scant as it is, suggests that this figure may not be too high. The following paragraphs summarize illustrative examples that have been identified in the literature search and contacts with practitioners in the field.

Perhaps one of the most visible examples of well contamination and related public debate has been the town of Burlington, Massachusetts. In the late 1960s, Burlington experienced the contamination of wells as a result of road applications and storage. The main water station was closed down because of a chloride content of 283 mg/l. According to estimates prepared by the U. S. Geological Survey, 40% of the contamination problem could be attributable to salt use (both application and storage) by the town of Burlington, 30% to applications by the Massachusetts Department of Public Works (primarily on Route 128, a major circumferential artery), and 15% to applications by the neighboring town of Lexington. The remaining 15% was attributed to septic tanks and industrial contamination.

City officials indicated no particular costs as a result of the shutdown of the main water station, since production from nine other wells less affected by the contamination problem could be increased to cover the demand. Other than outlays for an engineering study to determine the causes of the problem and identify simple remedial measures (approximately $15,000), no additional costs have been recorded. This particular statement, probably neglects a number of costs that may have been incurred, such as the actual costs of closing the well, incremental costs of increasing production from other wells, more frequent testing during the period of higher contamination levels, outlays for the changes in the drainage system recommended in the engineering study (114), and any costs that have been incurred as a result of intensive debate in the town regarding the advisability of a ban on street salting which was subsequently implemented for a two-year period. While these costs may be comparatively small for a town with 20,000 inhabitants, similar costs for the nation as a whole could be sizeable.

A different situation occurred in Goshen, Massachusetts, which experienced the contamination of seven wells which are owned privately, and one well owned by the local school committee. The source of the problem has been primarily the application of salt on nearby Route 9, also a highly frequented highway. The contamination was first noted in 1972; subsequent readings have failed to show any significant improvement. Several homeowners whose wells were affected by the contamination problem have placed their homes for sale at expected losses to them. (Further investigation could not determine the size of these expected losses.) Others have incurred significant costs for drilling new wells and replacing pumping equipment and pipes.

The School committee was forced to close the contaminated well and purchase bottled water for the school years between December 1971 and March 1973, a total cost of $650. The state has responded to the problem by building a drainage system along a quarter mile stretch near the affected wells in order to carry the salt runoff further down the road. This effort was partially successful for the wells affected, but resulted in the contamination of yet another well. Efforts by the town to have the wells replaced by the state have failed.*

Two final examples may round out this review of some of the evidence gathered in the study: two towns in Massachusetts, Weston and Norwell, both experienced severe contamination of their water supply because of salt application and storage. As a result, their wells had to be closed. The new wells cost approximately $150,000 in each of the two towns.+

Given this evidence, the estimate obtained above on the basis of more detailed data for the State of New Hampshire does not appear to overstate the total direct costs incurred by society and individuals as a result of the contamination of water supplies through deicing salts.

Indirect Costs --

The evaluation of indirect costs of salt contamination of drinking water supplies is hampered by conceptual problems, as indicated above, and by more severe data problems. Many of the examples of well contamination that have been encountered were defined in terms of chloride levels. Comparatively little is known about the incidence of sodium. While data on chloride levels are widely available (and have been used to study the relationships between road salting and water contamination), comparatively little has been done to monitor sodium levels. Any inferences concerning the relationship between road salting and sodium contamination therefore rely on the "rule of thumb" that sodium reaching water supplies is approximately one-third to two-thirds of the corresponding amount of chlorides.

These factors make an assessment of the absolute magnitude of health effects a rather uncertain undertaking. Review of water quality monitoring data indicates that in Massachusetts, approximately 27% of the towns and cities have one or more water supplies with a sodium level above 20 mg/l which can be taken as a cutoff point beyond which the water may constitute a serious health problem for the 4% to 5% of the population on low-sodium diets, or the 10% to 25% who have been estimated to be affected by hypertensive conditions. However, very little evidence in terms of epidemiological studies relating cardiovascular diseases (primarily hypertension) to sodium in drinking water is available. Part of the problem is that the recognition of the role of sodium in cardiovascular disease has been established firmly only recently.

Research on the relationships between characteristics of drinking water and cardiovascular diseases focused originally on the hardness of water. In 1960, Shroeder published a paper showing a negative correlation between the water hardness of potable water and cardiovascular deaths. This finding was confirmed in a number of subsequent studies. A study published

* Personal communication with the Chairman of the Board of Health, Goshen, Massachusetts, May, 1975.

+ Personal communications with Massachusetts Public Health Department, May, 1975.

in 1967 in a Russian medical journal (329) indicated a statistically significant difference in the incidence of hypertension among two groups, one using water supply with a "normal" amount of sodium, the other using water supply with an "elevated" sodium content. These results are somewhat problematic to interpret since "normal" and "elevated" were insufficiently defined. According to Wolf and Moore (145), "normal" in this article referred to a sodium level of 263 mg/l and less, while "elevated" sodium concentrations were in the range of 470-1180 mg/l. These levels are not typical for sodium concentrations in drinking water attributable to deicing salts.

Wolf and Moore (145) used data for areas in Dallas County, Texas to examine the possibility of any association between sodium content of the drinking water and cardiovascular deaths. Grouping communities into low sodium water supplies and high sodium water supplies, the authors then compared weighted average (cardiovascular) death rates per 100,000 for the two groups. The results of this comparison are shown in Table 4. Except for men in the age group 45 - 59, death rates are significantly higher for the high sodium communities. The authors suggest that the exception may be due to the fact that men in this age group tend to be economically active, spending a major portion of their time in the city of Dallas (a low sodium community).

The implications of these differences in age-specific death rates can be illustrated by examining their implications for a sample group. For the 60 - 74 age group, the difference in death rates between low and high sodium communities is 400 per 100,000, or .004. If this figure holds generally, the age-specific survival rate would be lowered by this differential. For men in the age group 60 - 64, the national survival rate is approximately .835. This rate corresponds to an average life expectancy for men in this age group of 5.6 years. If the survival rate is lowered by .004 to .831, the average life expectancy declines to 5.4 years. Higher levels of sodium concentration in the drinking water thus would imply a reduction in the life expectancy for this age group by almost 4 percent. Extrapolating these data to the national level is impossible because of the limited nature of the study and because of lack of data relating to the incidence of sodium concentrations in drinking water over a sufficient time period.

An indicative estimate of the cost of salt contamination of drinking water supplies in terms of their health effects can be obtained by estimating the expenditures required to remove the hazard. A rough assessment of the total cost can be obtained by assuming that all people affected by conditions of hypertension would purchase bottled water for drinking purposes, once their water supply exceeded a sodium concentration of 20 mg/l. For the normal adult, an average drinking water consumption of 2.2 liters has been estimated. This estimate can be used to obtain a rough estimate of the potential cost of supplying all persons on low-sodium diets affected by sodium concentrations over 20 mg/l with bottled water. A gallon (3.8 liters) of bottled water sells currently for about $.50. The average person would therefore spend approximately $106 (2.2/3.8.365.50) per year to satisfy his or her drinking water needs entirely through bottled water.

Table 4

Differences in Cardiovascular Death Rates
For Different Levels of Sodium in Drinking Water
(per 100,000)

Age Group	High Sodium*		Low Sodium+	
	Males	Females	Males	Females
45 - 59	375	91	447	74
60 - 74	1,730	990	1,330	570

* 120 mg/l or more
\+ 25 mg/l or less

The number of persons on low sodium diets exposed to sodium concentrations in the drinking water above 20 mg/l attributable to road salt is extremely difficult to estimate. The Massachusetts' experience indicates that approximately 27% of the water supplies (not necessarily the population) are affected by high sodium concentrations attributable to road salt. As a broad estimate, it can be assumed that roughly 25% of the population under conditions similar to those in Massachusetts are affected. Four percent of the population have been estimated to be on a low-sodium diet. Using salting intensity as a weight to make other states in the snowbelt comparable to Massachusetts yields an estimated total cost for the nation of $105 million. Since Massachusetts relies more heavily on groundwater than the nation as a whole (23% vs. 21%), the estimate should be somewhat lower, i.e., $96 million.

In summary, the direct and indirect costs of water supply contamination may add up to almost $150 million nationwide. This figure provides an impression of the magnitude of the damages, rather than describing actual costs. It should be noted that the considerations in this section do not include any costs to industry as a result of special requirements for processed water.

5.3 COSTS OF DAMAGES TO VEGETATION

Experiments and empirical studies have clearly demonstrated that (a) many of the trees used for roadside planting in the snowbelt (notably sugar maples) are sensitive to increased sodium concentrations in the soil, and (b) there is a direct link between the deterioration or death of roadside vegetation and salt application.

Essentially, roadside vegetation (whether public or private) may suffer as the result of two major factors. First, vegetation may be affected by the runoff of salt brine and the retention of sodium ions in the soil. This possibility is particularly acute in highway stretches characterized by conditions that favor a fast runoff of salt brine from the road surface to the area of vegetation, combined with a comparatively poor drainage in the area itself. The second possibility, which impacts particularly upon shrubs and hedges in urban areas, is the practice of dumping salt-saturated snow along the edges of the road, after plowing. This practice may lead to extremely high salt concentrations around the plants affected. Since many of these plants are characterized by shallow root systems, and since much of the sodium remains in the upper layers of the soil, destruction of shrubs and hedges is a common occurrence.

However, most of the research on the effects of deicing salts on roadside vegetation has focused on the damages to trees along suburban and rural roads. The affected strip extends approximately 9 to 12 m from the edge of the road. Salt concentrations beyond this distance in the soil have been found to be negligible. Within this strip, salt affects vegetation in two ways. First, it directly interferes with the chemical processes by which plants absorb nutrition; it affects the osmotic balance, thus inhibiting the water intake of plants, and it may replace vital nutrients. In addition to these direct effects, sodium in the soil may also result in a rapid deterioration of the soil itself. According to Westing (191), "...when sodium comes to occupy more than about 15% of the total cation exchange capacity of the soil, soil structure begins to deteriorate. ...permeability and water-holding capacity decrease markedly."

While the botanical and chemical evidence is sufficient to suspect widespread deterioration of roadside vegetation in areas characterized by the heavy use of deicing salts, the empirical backup is somewhat meager. Aside from studies of specific stretches of highway and their vegetation (such as Button [156, 157]), the data base relating to the interaction between deicing salts and vegetation damage at a macroscale is limited to reports of specific instances. For example, Rich (175) reports that in 1957, the New Hampshire Highway Department removed 13,997 dead trees along 3,700 miles of highway. The estimated cost of removal was $1 million or more than $70 per tree. According to other reports, Winchester, Massachusetts, which has applied as much as 55 tons of salt per mile, has lost an average of 56 trees per year since 1963. (26) Similarly, Newton, Massachusetts which also tends to apply salt amounts far above the average for towns and cities in the state, is reported to have lost about 500 trees per year between 1965 and 1970 (40).

The problem with the evaluation of these reports is that they tend to relate tree deaths from all causes to salt application. Since no national statistics are available concerning the number of dead trees per year, it is impossible to identify the net effects of deicing salts in terms of damages to roadside trees statistically. Similarly, data on the population at risk (i.e., roadside trees possibly exposed to deicing salt runoff), which would be useful in applying micro-analytical findings to a macro-level framework, are unavailable.

As a result, national damage estimates simply cannot be generated. The following discussion therefore explores possible cost ranges, including both direct and indirect costs associated with tree damage that can be related to deicing salts. Direct costs relate to the cost of maintenance and removal in the case of death, while indirect costs concern the losses in welfare to society or individual property owners resulting from the disappearance (or deterioration) of a fully grown shade tree, which may or may not be replaced by a small young tree. From a conceptual point of view, it is of course the evaluation of indirect costs that constitutes the most difficult task.

Fortunately, a number of studies have been undertaken to determine the monetary value of shade trees. According to the International Shade Tree Conference (169), three basic factors must be considered in determining the monetary value of a shade or ornamental tree: size, kind and condition of the tree. Tree size is generally measured in terms of diameter at breast height (dbh), where breast height is defined as 1.37 meters above ground. In August, 1973, the International Shade Tree Conference adopted $10.00 per square inch (1.55/sq. cm) of truck cross-section as the conservative value of a perfect specimen shade tree. Table 5 presents the base values of shade trees for different dbh values. This material would imply, for example, that the indirect costs associated with the New Hamsphire example mentioned above would add about $10 million to the direct costs (using a fairly conservative average of 10-inch (25.4 cm) dbh for the 13,997 trees removed.)

While the measures established by the International Shade Tree Conference may be somewhat arbitrary and, more importantly, apply primarily to urban trees, they provide an indication of the potential magnitude of the problem. If only 6% of all tree deaths in the New Hampshire example can be attributed to deicing salts, the total cost figure, including both direct and indirect costs, would be comparable to the total costs computed for the water contamination damages, or $46.5 million.

Table 5

Basic Values of Shade Trees
(For Perfect Specimen Shade Trees)

Trunk Diameter Inches	Cross Section Area Square Inches	Basic Value (in Dollars)*
2	3.14	31
5	19.64	196
10	78.5	785
15	176.7	1,767
20	314.2	3,142
25	490.9	4,909
30	706.9	7,069
35	926.1	9,621
40	1,256.6	12,566
45	1,590.4	15,904
50	1,963.5	19,635
55	2,375.8	23,758
60	2,827.4	28,274

*Calculated on the basis of $10.00 per square inch (1.55/sq. cm) of cross-section trunk area at 4.5 feet (1.37 m) above ground.

(Note: One inch = 2.54 cm; one square inch = 6.45 sq. cm.)

5.4 COSTS OF DAMAGES TO HIGHWAY STRUCTURES

Deicing salts contribute to the deterioration of bridges, decks and supporting structures, highway surfaces and other highway structures. The review of the available evidence on the physical and chemical processes involved, presented in Section 4.2.2, provides the background for an exploratory assessment of the cost implications of the incremental damage caused by deicing salts. This assessment focuses on bridge decks, since the technical evidence of causal relationships is most convincing in this case.

The true cost to society of salt-induced bridge damages includes direct outlays by highway departments for activities such as inspection, repair, and replacement, as well as indirect costs to the public including that portion of Federal research outlays, vehicular deterioration, lost time, and increased accidents which may be attributed to the use of salt (e.g., rear end collisions in traffic lines resulting from repair work). This section first summarizes the direct costs, presents a partial analysis of the indirect costs, and finally gives an estimate of the full social costs of salt damage to the nation's highway bridges. The cost estimation approach is characterized by extreme conservatism; areas in which the available evidence or required data are either not available or not sufficiently reliable are treated with deliberate skepticism. This procedure implies that the total cost estimate describes the lower boundary of the actual costs.

5.4.1 Direct Costs

The actual cost outlay by state highway departments for the repair of bridge decks was estimated to be $40 million or more in 1971. (230) This estimate of private costs is conservative in that it ignores the costs of installing improved design features such as waterproof membranes in new bridges, and also because maintenance on spalling decks has been insufficient to maintain a constant average quality. The result is a substantial understatement of true costs. Outlays for repair that would halt the deterioration in quality were estimated by Kliethermes to be some two to three times actual expenditures, or $80 to $120 million*

Recent evidence from individual states, particularly West Virginia, provides a check on Kliethermes' cost figures. The cost of maintaining West Virginia's 6,000 bridges in good condition was recently estimated to be approximately $12 million, or about $2,000 per bridge. The number of bridges affected by salting of the nation's highways can be derived from a map in the Kliethermes article (230) which depicts regions of severe, moderate, and no deterioration throughout the country.

* Personal communication with J. Kliethermes, Federal Highway Administration, December, 1974.

Although the total number of highway bridges was readily obtained, the number in each state could not be determined, and it became necessary to estimate their distribution. Following a suggestion of Adrian Clary*, of the Transportation Research Board, the distribution of bridges was estimated in proportion to the distribution of the human population throughout the country. Using Kliethermes' data on regional damages as shown in Figure 13 and assuming that 100% of the bridges located in severe regions require periodic maintenance and repair of salt induced damages, whereas only 20% of the bridges in moderate regions are so affected, we conclude that nearly 100 thousand bridges are adversely affected. Assuming that the West Virginia estimates are representative of costs in other severe deterioriation regions, a yearly cost for the nation's bridges of $200 million is estimated+.

This of course provides only a rough overall estimate. A more differentiated approach, using microeconomic cost data for each of the possible activities related to the detection of salt-related damages, and resulting repair and replacement, could be employed to explore the implications of alternative damage configurations for highway bridge decks. The microeconomic cost data are summarized in Table 6.

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* Personal communication with Adrian Clary, November, 1974.

\+ During the winter of 1969-1970, West Virginia used an average of 3 tons of salt per lane mile and 20 tons of salt per bare pavement lane mile. (Not all roads are required to be kept bare; thus these figures may be very different in some states.) Many other states in the snow belt exceeded these figures, for example:

State	Salt Per Lane Mile (tons)	Salt Per Bare Pavement Lane Mile
Connecticut	33	33
Maine	8	20
Massachusetts	35	35
New York	19	19
Pennsylvania	11	34
Maryland	19	31
Ohio	25	25
Illinois	10	19

These figures indicate that the problems in West Virginia might be expected to be less serious than in other snow belt states; and, consequently, the costs of maintenance and repair may be higher in other states.

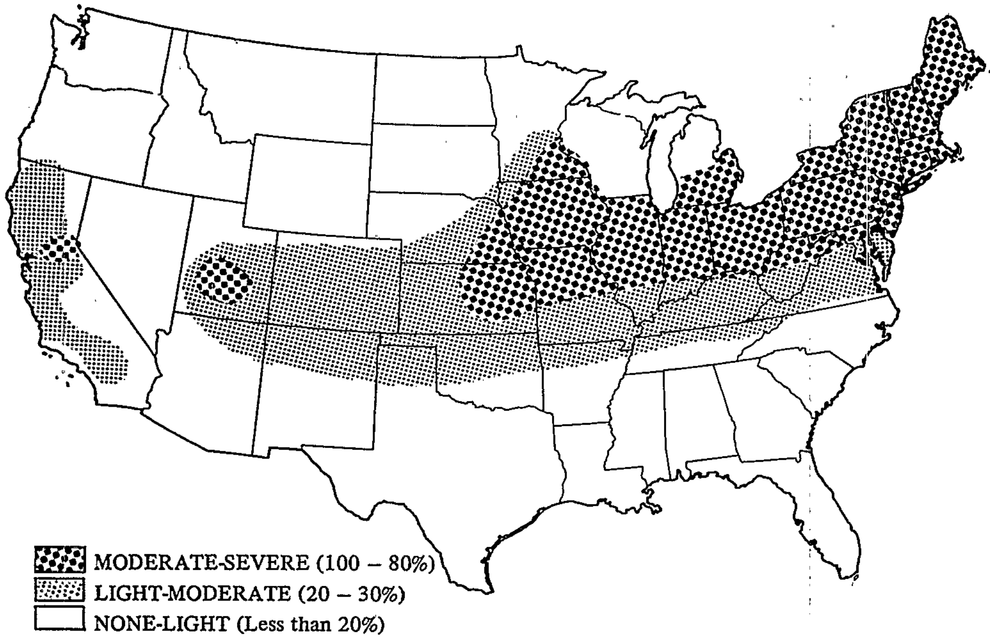

Figure 13 Corrosion of reinforcing steel in highway structures (from Kliethermes, Reference 230)

Table 6. Summary of Microeconomic Costs

Activity	Estimated Cost per Square Foot	Estimated Life Expectancy
Visual Inspection	Nominal	One year
Chloride Detection	Variable - $.25	Variable
Maintenance Patch	Variable - $.50+	Few months to few years
Restoration	$9.00	Up to 15 years
Replacement	$15.00	Up to 50 years
New Techniques:		
Polymer Impregnation	$1.	Up to 50 years
Membranes	$1.	Up to 15 years
Epoxy coated steel	$1.	Up to 50 years
Latex modified concrete	$.50	?
Wax in concrete	$1.	?
Cathodic Protection	$.50+	Up to 50 years

All figures in the table are to be taken as estimates, and were derived from the available literature, consultation with highway department officials, and our judgment as to the probable trend of costs once a technique becomes proven (viz. cathodic protection whose costs in large scale use are largely unknown - but may be quite low). The life of a bridge is taken to be 50 years in a salt-free environment -- thus no activity could be expected to produce a life expectancy greater than 50 years.

It should be noted that the estimates provided include not only maintenance and repair costs, but also incremental costs of preventive measures through the improvement of construction techniques for new bridges. The technical discussion of bridge-deck repair in Section 4.2.2 reviews the experimental evidence that polymer impregnation of concrete is quite cost-effective; given its extreme durability it will probably become the most inexpensive method of protecting new concrete decks. The annual cost of incorporating polymer-impregnated concrete in all new bridge decks constructed in the snow belt can be estimated by multiplying the number constructed each year by their average size by the cost per square foot. Annual construction volume in the snow belt ranges from 1,000 to 1,500 bridge decks, with an average size of about 8,800 square feet (818 sq. m.)* At a cost of roughly $1 per square foot, ($11/sq. m.) the total cost would be approximately $9 to $13 million.

Adding the incremental cost of bridge-deck construction required to prevent salt damage to the estimated maintenance costs thus yields a total direct cost figure for bridge decks alone of approximately $210 million. Again, it should be emphasized that this estimate is based on very conservative assumptions. Projecting these costs into the future is difficult. While preventive measures are likely to reduce the need for maintenance and repair, the exact reduction in the latter costs is uncertain. In addition, given the total number of bridge decks and their maximum life expectancy, it would appear that the current annual construction volume is insufficient to replace all of the bridge decks within the time period of 50 years. Stepping up construction activity would result in corresponding increases in the costs of prevention. Based on these considerations, and the cost estimates derived above, it is reasonable to assume that the annual direct costs associated with salt damages to bridge decks will be in the neighborhood of $200 to $250 million annually in the next few years.

This figure refers primarily to bridge decks. In addition, the relevant direct costs attributable to salt-induced damages should also include the costs of necessary repairs because of structural damages. While these damages are insufficiently documented for the nation as a whole, specific

* According to Richard Hay of the Federal Highway Administration.

instances can be cited to provide an impression of the potential magnitude of this problem. For example, damages to the West Side Highway Viaducts in the Borough of Manhattan in New York City were severe enough to require rehabilitation efforts at a cost of approximately $96 million, or almost $50 per square foot ($4.65/sq. m.) of highway*. While this particular example may be exceptional, it illustrates the possible magnitude of additional costs associated with major damage cases related to salt use.

5.4.2 Indirect Costs

The direct cost estimates include only expenditures by highway agencies for special design features on new bridges and the repair of existing structures to counter the adverse effects of road salting. Full social costs would include delays to motorists during repair, repair costs for damages to ball joints and front end alignment from travel on uneven bridge surfaces, and the cost of accidents which are attributable to rough bridge deck surfaces. Some of these latter costs, though potentially important, would be exceedingly difficult to measure accurately. Therefore, the analysis here focuses on the value of lost time.

The discussion of vehicle behavior at sites of traffic obstruction in a recent OECD report (260) provides a basis for estimating time loss during bridge repair. In the hypothetical example to follow, a typical repair of a three lane bridge deck (each way) in an area subject to congestion at rush hour is examined. As such it probably represents a maximum estimate for time loss during bridge repair. Obstructions such as bridge repair lower highway capacity. Studies of freeway traffic in Los Angeles indicate that the capacity of a three lane highway that has been constricted to two lanes is reduced from a range of 4,000 to over 5,000 vehicles per hour to the lower range of 2,400 to 3,200 vehicles per hour. Congestion feeds upon itself; as traffic begins to slow, drivers will respond by more frequent lane switching and other maneuvers that only serve to aggravate the situation+ . (260)

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* The engineering reports cited deicing salts as one of the major factors contributing to the structural weakening of the bridge. See: Hardesty and Hanover, Consulting Engineers: Reports on the Inspection and Analysis of the West Side Highway (Miller Highway). For the City of New York, Department of Highways, Contract No. THXM 152E, Capital Project No. HW19. Four reports October, 1974-May, 1975. (References 221, 222, 223, 224).

+ This example excludes a myriad of technical questions. Other factors which affect traffic flow include: (1) the length of the obstruction, (2) the control of traffic speed at the obstruction, (3) controlled gaps in the flow which may actually increase the capacity of the obstructed section, and (4) the opportunity for using reversible lanes can significantly reduce the impact of the obstruction.

Figure 14 portrays the hourly traffic capacity and demand for inbound vehicles and Figure 15 the cumulative capacity and demand for this highway. Total waiting time for vehicles using this road segment is given as the shaded area between the given capacity of the system and cumulative demand on the system. The delay for traffic entering at a given hour is given by the horizontal distance between the cumulative demand and cumulative capacity. The total area between the two curves may overestimate actual waiting time to the extent that motorists are diverted to uncongested alternative routes. If motorists' decisions to use alternative routes also produce congestion on the alternative routes the estimate could conceivably be understated. In this example, total waiting time before the lane obstruction is 4,000 hours, and after the lane restriction about 17,200 vehicle hours. Valuing an hour's wait at $3.00 per hour provides an estimate of $51,600 per day.* Assuming the repair requires 50 working days, and that repairs to outbound lanes will require similar delays to motorists, the total cost of delay may be estimated as in excess of $5 million. Although delay costs of this magnitude may be extreme, several such instances probably occur in or near large metropolitan regions every year. Until better data are available on the actual number of bridges being repaired and the typical time delays involved, no accurate national cost figures can be reported for motorist's delays.

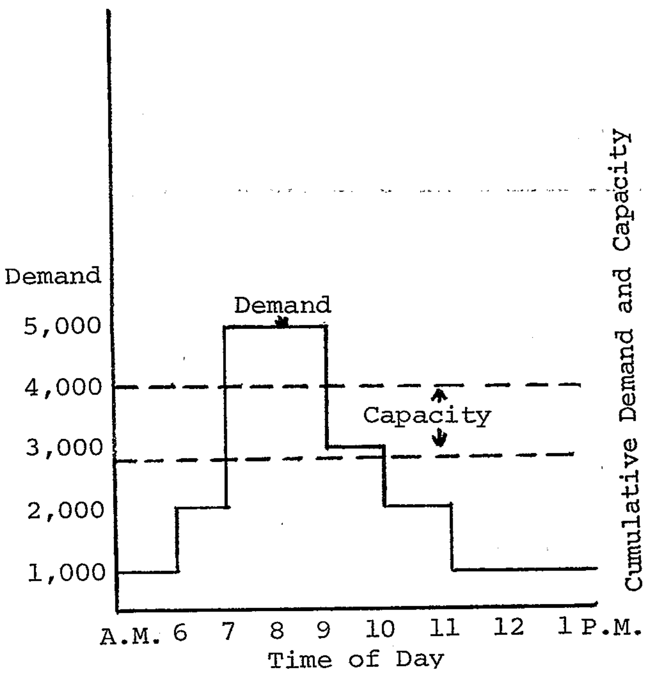

Figure 14. Hourly Traffic Capacity and Demand

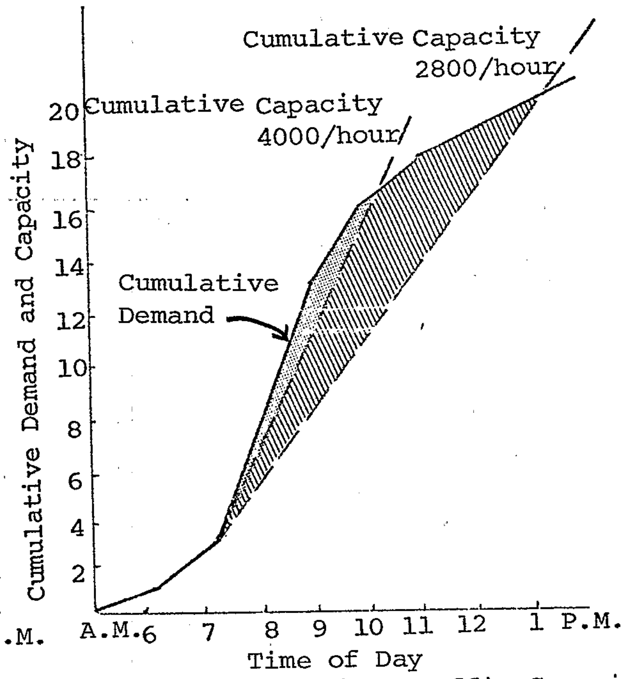

Figure 15. Cumulative Traffic Capacity and Demand

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* Economists (see Owen, "The Value of Commuter Speed," Western Economic Journal, June 1969) have argued that the costs of delay increase more than proportionately with the length of the delay. The $3.00 figure is an approximate average of the costs of short and long delays.

5.4.3 Estimates of Total Costs

While it is difficult to get a firm handle on the relevant cost categories, both direct and indirect, for evaluating the national costs of salt-related damages to bridge decks, the available information is sufficient to suggest that society incurs substantial costs as a result of bridge deck deterioration. A very conservative estimate of the direct costs of rehabilitative and preventive measures associated with this problem places the total national cost at close to $250 million. The analysis of one indirect cost category yields estimates of up to $5 million for a single bridge. Since nearly 100 thousand bridges are affected by required repairs, even a low probability of occurrence of such costs attributable to increased waiting times as a result of lane closings for repairs would still yield substantial total costs. Even if only one bridge in 2 thousand (.05%) were similarly affected, the total indirect costs of increased waiting times would amount to $250 million. These extreme costs are admittedly very infrequent. However, it is likely that smaller waiting costs are incurred at more bridges. An estimate of $250 million for the indirect costs of waiting therefore is probably again on the low side.

In summary, the total annual costs of bridge deck damages related to salt use can be estimated to exceed $500 million.

5.5 COSTS OF AUTOMOBILE CORROSION

Sufficient evidence has been presented in Section 4.2.1 to support the assertion of a causal relationship between deicing salts and corrosion of automobiles. This corrosion in turn results in a variety of costs to automobile owners. Four major cost categories can be distinguished:

- costs of protective measures both by manufacturers and by owners;
- costs of repairs required to maintain the ability of the automobile to function at the same level as without salt-induced corrosion;*
- losses in economic value of the automobile as a result of salt-induced corrosion; and
- costs of accidents attributable to automobile malfunctioning associated with salt-induced corrosion.

The first category presents a number of difficulties in measuring the relevant costs. The main problem is the attribution of design changes or other protective measures to the salt problem. Any measure of costs in these categories is therefore fraught with considerable uncertainties.

* The relevant costs here refer only to that portion of outlays required to restore the corrosion damage which actually impairs the level of service provided by the automobile.

In the interest of reliable cost measures, this category will not be included as an integral part of the total cost estimate.

A similar reasoning applies to the second cost category. It is difficult to assess the degree to which expenditures on repairs are actually required to restore or maintain the automobile's ability to provide the same level of services as in a salt-free environment. Generally, relevant repairs tend to go beyond the required level. In addition, expected repair costs associated with salt-induced corrosion are reflected in the loss of economic value of the automobile.

The third category is the most important one, since it is possible to attribute depreciation rates to the influence of salt. Under the general assumptions of economic theory, the loss in economic value accurately reflects the expected costs associated with a reduction in the automobile's ability to provide the desired services. These expected costs include direct outlays for restoring at least part of the loss. While the ideal conditions assumed in economic analysis (such as perfect information without uncertainties) are consistently violated in the real world, the concept of the loss in economic value reflecting expected future costs (or losses in benefits) is sufficiently broad to cover the full spectrum of monetary equivalents of the corrosion damage caused by deicing salts.

In fact, the concept is comprehensive enough to include the likely costs of accidents, the fourth category of costs. Provided the consumer is able to assess the likelihood of an accident as a result of corrosion damages to certain components of the automobile, the reduction in economic value of the car includes the expected costs of such accidents (or in risk associated with this cost category). This interpretation is useful, since it eliminates the need for an estimation of the highly uncertain costs of accidents attributable to salt-induced corrosion damages.

These considerations determine the approach presented here. The analysis first examines the formal framework for expressing depreciation rates as a function of the use of deicing salts. This discussion is followed by an empirical analysis of the relationship on the basis of used car prices in different Standard Metropolitan Statistical Areas (SMSAs) of the country. The section concludes with an assessment of the costs of undercoating and other preventive or restorative measures.

5.5.1 Depreciation of Automobiles

The analysis of the relationship between original purchase price and current value of a car (as described by the current market price) can draw on established models in capital theory. Ackerman (268) has developed such a model of used car prices. This model is sketched in Appendix B; it results in a simple exponential decay expression with a constant depreciation rate:

(1) $$P(v)/P(0) = Be^{-av}, \quad \text{or } P(v) = P(0)Be^{-av}$$

where $P(v)$ = the current price of the car
$P(0)$ = the original purchase price of the car (new)
v = age of the car
B = a constant
a = the constant depreciation rate

On the basis of data on prices of cars at age v and their corresponding original purchase prices, the two unknown coefficients in this expression B and a -- can be estimated by applying ordinary least squares to the logarithmic form of the depreciation function:

(2) $$\ln P(v) - \ln P(0) = \ln B - av.$$

The major data source for prices of used cars are the guidelines prepared by the National Automobile Dealers Association (NADA) which are published on a regional basis. Ackerman (268) estimated the coefficients of Equation (2) using NADA prices from the July price books for the period 1956 to 1965 for several makes and two production years (1956, 1958). She obtained the following results for the constant depreciation rate, a:

Make	Annual Depreciation Rate
Chevrolet (1956)	27.9%
Ford (1956)	29.4%
Plymouth (1956)	34.2%
Chevrolet (1958)	28.8%
Ford (1958)	29.7%
Plymouth (1958)	33.2%

This model of used-car prices establishes a framework for assessing the effects of external factors on the overall depreciation rate. This assessment is based on the assumption that the depreciation rate, a, in Equations (1) and (2) is not a constant for a given make and production year, but varies by geographical region in response to environmental conditions (such as climate or the use of deicing salts), use and maintenance practices for the car, and prevailing preferences and tastes. Observations on these factors require a much smaller level of aggregation than implicit in the NADA regions. The unit of observation used in the analysis here is therefore a city; the discussion below describes sample selection and data-gathering procedures, following a review of the likely impact of different factors on automobile depreciation.

Environmental Factors: Characteristics of the physical environment in which the car is operated directly affect corrosion and thereby the loss in economic value. These characteristics include ambient temperature, atmospheric humidity, sulfur dioxide concentration in the atmosphere, and other pollutants that are known to contribute to corrosion. Similarly important is the incidence of cases in which automobiles are exposed to moisture, such as measured by rainfall or snowfall.

Finally, an important factor concerns the characteristics of roads on which the cars are driven. These characteristics may include elements such as road surface and road dirt. Most road dirt, for example, clings to parts of the automobile body, retains moisture and thereby fosters the process of corrosion. Similarly, loose aggregate may result in scratches in the body finish, making it vulnerable to corrosion. Unfortunately, this factor is almost impossible to measure except in an experimental situation. The most important road characteristic, at least for the purpose of the investigation here, is the incidence and intensity of deicing salts on the road surface.

Use and Maintenance of Cars: The depreciation of a given automobile depends to a large extent on its expected useful life, which in turn reflects its past use as well as any maintenance efforts by the owner. One important factor is the mileage the car has been driven. Another factor is the frequency and thoroughness of washing the car, which may delay corrosion by eliminating pockets of dirt and moisture as well as removing salt from the body or structural parts of the automobile.

Again, many of the relevant aspects of use and maintenance cannot be measured at an aggregate level with any degree of accuracy. For example, there are few if any data on the frequency and thoroughness with which a car is being washed. Similarly, the extent of garaging -- which may modify the importance of ambient temperature as a determinant of corrosion -- is unknown on a large-scale basis.

Tastes and Preferences: It is entirely possible that differences in depreciation rates among cities reflect little more than interregional differences in terms of preferences for new vs. used cars. For example, areas in which public transportation provides an efficient alternative to the private automobile, two-car families may be rare. Alternatively, in areas in which a second car is owned by many families, the structure of tastes and preferences may be such that the demand for used cars is strong and used car markets are active.

No reliable indicators of such regional differences in tastes and preferences exist. While the potential importance of these factors in determining the rate of depreciation of cars is recognized, the analysis here therefore does not attempt to isolate this particular factor.

Specification of the Regression Equation: The influence of the type of factors examined in the preceding paragraphs on the depreciation rate for automobiles has been examined through multiple regression analysis designed to test the existence of any functional relationships of the form:

Depreciation Rate = f(Environmental Factors, Use of Maintenance, Tastes and Preferences)

Primarily, for reasons of simplicity, the linear additive form of this functional relationship was examined to isolate the net effects of deicing salts. The specification of a linear relationship between the depreciation rate and independent variables clearly is questionable for certain variables, as illustrated by means of an example, under the simplifying assumption that depreciation is directly related to corrosion of structural parts or the body of the car. It is known that the rate of chemical reation (i.e., corrosion of steel) is temperature dependent: the rate of reaction doubles for every 10°C increase in ambient temperature--clearly a non-linear relationship. The linear relationship hypothesized in the regression model may not be a close approximation, even over the relatively narrow range of temperatures that are encountered. However, the specification error may be relatively small compared to the inherent measurement error. It is extremely difficult to determine the appropriate temperature measurement to use for assessing its impact on corrosion. Is it the temperature of a heated garage in winter (a major factor contributing to corrosion), the average ambient winter temperature, or some annual mean? The actual effect of temperature is therefore difficult to determine.

The relationship for other variables such as salting intensity is probably specified in the theoretically correct form. Tests discussed earlier by the APWA and NACE indicate that the corrosion rate increases approximately linearly in the range of salt concentrations encountered by automobiles in typical winter driving conditions. Overall, given the current understanding of the determinants of corrosion and their effects on automobile depreciation, no alternative specification of the equation used in the regression analysis appears more appropriate than the linear one.

5.5.2 Data Collection for Empirical Analysis

As already mentioned above, the data on used car prices available through NADA price books are at too aggregate a level to be useful in testing the effects of the three types of factors distinguished above. The analysis here, therefore, requires estimates of the depreciation rates for the same make of vehicle in different environments to allow for the use of characteristics of these environments to "explain" the variation, if any, in the rates. A suitable definition of environment refers to cities in the continental U.S.

Estimating decay rates, in the same way as Ackerman (268), for different cities is complicated by problems of data availability. This approach would require sufficiently accurate statistics on used car prices for a relatively long period of time, such as ten years, for each city. Such statistics can be obtained from newspaper advertisements, but the labor requirements for searching newspapers from an adequate number of cities over such a time period are prohibitive. However, given Ackerman's findings, the data requirements for the analysis here can be reduced substantially. Since these findings suggest that the exponential depreciation model with constant rates fits reasonably well, representative depreciation rates can be calculated on the basis of new car prices and a single observation on a used car price.*

The procedure followed to estimate decay rates was to obtain several price observations (30 on the average) on each of the three makes of used cars in 44 metropolitan regions, and to calculate the rate of depreciation for each observation required to yield the used-car price. For each city, a representative depreciation rate was calculated as the simple arithmetic average for the respective observations. These estimates are shown in Table 7 . All of the estimated rates are lower than those reported by Ackerman and shown above. This may be partially due to the composition of the sample of car makes: Chevrolet Bel Air, Chevrolet Impala, and Volkswagen. The inclusion of Volkswagens, which depreciate at unusually low rates, lowers the overall average. In addition, there is the possibility that estimates of new car prices are somewhat inaccurate. However, neither of these factors should affect the estimated variation in depreciation rates across cities; in other words, there is no reason to believe that such measurement errors would introduce any bias into the sample.

Table 7 presents depreciation rates by broad categories of exposure to deicing salts. There is a fairly consistent trend across the three categories distinguished: depreciation rates rise as the intensity of salt use increases. However, this trend should not be overemphasized: the measured depreciation rates may be inaccurate, or other factors that are actually responsible for interregional variations happen to be correlated with salt use.

The accuracy of asking prices in newspaper advertisements as a measure of the market value of a used car is certainly open to questions. Prices actually paid are likely to be lower than asking prices. As a data reliability check, average newspaper asking prices for certain makes (primarly 1967 Chevrolets) were computed for regions corresponding to

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* New car prices were estimated as 90% of suggested list price plus dealer preparation costs and transportation charges. Adjustments for optional items (e.g., air conditioning) were made, if advertised.

Table 7

Estimated Depreciation Rates for Selected Cities

Salt more than 25 tons per lane mile		Salt between 5 and 25 tons per lane mile		Salt less than 5 tons per lane mile	
Hartford, Conn.	23.5	Wilmington, Del.	22.1	Phoenix, Ariz.	19.4
Chicago, Ill.	24.2	Indianapolis, Ind.	22.1	Los Angeles, Cal.	19.8
Portland, Me.	25.1	Des Moines, Ia.	21.2	Denver, Col.	21.5
Baltimore, Md.	23.3	Augusta, Me.	26.8	Tampa, Fla.	20.1
Boston, Mass.	24.1	St. Louis, Mo.	22.0	Atlanta, Ga.	20.2
Springfield, Mass.	23.5	Omaha, Neb.	21.3	Gt. Falls, Mont.	20.1
Detroit, Mich.	25.1	Newark, N.J.	2.18	Reno, Nev.	21.8
St. Paul, Minn.	25.2	Oklahoma City, Oh.	22.4	Albuquerque, NM.	19.4
Concord, N.H.	26.9	Memphis, Tenn.	20.3	Portland, Ore.	19.5
Syracuse, N.Y.	26.1	Richmond, Va.	21.5	Charleston, S.C.	20.7
Cincinnati, Ohio	22.1	Laramie, Wyo.	22.6	Dallas, Tex.	21.5
Cleveland, Ohio	23.4			Seattle, Wash.	21.4
Philadelphia, Pa.	22.9				
Providence, R.I.	23.6				
Pittsburgh, Pa.	25.5				
Salt Lake City, Ut.	23.0				
Burlington, Vt.	26.6				
Milwaukee, Wisc.	22.7				
Mean	24.3	Mean	22.2	Mean	20.5

the NADA regions and compared to the NADA price guidelines. Within regions considerable variations in depreciation rates were observed: for example, within the New England region, Providence, Rhode Island showed a composite depreciation rate of 23.6%, while the corresponding rate for Concord, New Hampshire was 26.9%. Average prices for regions, though, were much closer to the NADA figures; in each case, the two prices were within 10%, with the typical difference being much less. Overall the newspaper prices averaged approximately 2% less than prices in the NADA guides. Since the actual prices for cars advertised in newspapers are likely to lie below the stated asking prices, the comparison indicates that the two markets differ substantially. Differences may be attributable to quality differences in the cars offered for sale, or to better resale preparation by used-car dealers.

These considerations established a set of observations for the dependent variable in the regression equation. As the discussion of the potential range of independent variables above indicates, within each of the three categories of factors distinguished, several measures can be used to describe the elements influencing regional variations in depreciation rates. The following measures have been selected for the analysis reflecting the principal emphasis on the importance of environmental variables as determinants of corrosion.

5.5.3 Environmental Conditions

State salt refers to the number of tons of salt applied per lane mile of bare pavement on state highways for the winter of 1969-1970. (Bare pavement is the highway engineer's term for pavement that is kept free of ice and snow year round through plowing and liberal application of deicing chemicals.) In cases in which salt usage for this winter differed substantially from that for the winter of 1966-1967 (the other year for which these data were compiled by the Salt Institute), the mean of the two figures was used.

City salt refers to the number of tons of salt applied per lane mile of bare pavement on city highways during the winter of 1969-1970. Cases with substantial differences between 1969-1970 and 1966-1967 were handled in the same way as described for state salt.

Snow fall has been measured in inches for the winter of 1969-1970 for each city. If this value differed by more than 25% from normal levels, the average snowfall for the three winters (1966-1967, 1969-1970, and 1970-1971) was used.

Temperature was measured as the mean ambient January reading for each city in degrees Centigrade.

Humidity/rainfall: humidity statistics proved difficult to obtain, and consequently rainfall in inches per year was substituted for humidity.

Proximity to ocean was included as a dummy (0/1) variable in the regression analysis.

Sanding intensity was measured as tons of sand applied per mile of highway in each state.

Air pollution was measured in the regression by a single variable, the annual mean concentration of sulfur dioxide in ug/m^3.

Use and Maintenance

As already discussed above, the measurement of many of the relevant aspects of use and maintenance of cars on a non-experimental basis is extremely difficult, if not impossible. The analysis therefore used only one measure, the average number of miles (in thousands) traveled by a vehicle in each of the states. Unfortunately, vehicle mileage was not available for the cars offered for sale.

Tastes and Preferences

The discussion above indicates that tastes and preferences themselves are almost impossible to measure in a way that would yield meaningful descriptors for the analysis here. In an attempt to include these possibly important characteristics, income per capita and vehicles per capita were used in the regression as imperfect proxies of the determinants mentioned above.

5.5.4 Regression Results

Given the limited understanding of the possible functional relationships between corrosion and car values, the corrosion and environmental factors, the regression equation was tested in its simplest, i.e., linear form, as discussed above. The approach was largely empirical, that is, all variables assumed to influence depreciation rates were used in different specifications as explanatory variables in the regression analysis. The following functional form showed the best performance:

$$\begin{aligned} \text{DEPRECIATION RATE} = 15.7 &+ \underset{(2.01)}{.038}\ \text{STATE SALT} + \underset{(3.03)}{.019}\ \text{CITY SALT} \\ &+ \underset{(3.67)}{.029}\ \text{SNOW} + \underset{(1.48)}{.170}\ \text{MILES} \end{aligned}$$

The figures in parentheses under the regression coefficients refer to the t-statistics of the coefficients, a measure of statistical significance.* The multiple correlation coefficients for this equation was .79, which implies that the variation of the four independent variables "explains" 79% of the variation of the dependent variable across the 41 metropolitan areas finally used in the regression analysis.+ The t-statistics shown indicate that both city salt and snow have coefficients that are significantly different from zero at the 99% confidence level; the significance level for state salt is 95%, while the coefficient of miles traveled is significantly different from zero only at the 90% confidence level. All coefficients have the expected sign.

None of the other explanatory variables used in the series of regression analysis runs showed any systematic relationship to the depreciation rate. A partial exception concerns the two indicators of tastes and preferences, income per capita and vehicles per capita. When either of these variables was included in the entire regression, the coefficients were not significantly different from zero. When used with the salting intensity and snowfall variables separately, the coefficients of both income per capita and vehicles per capita were significant, income having a negative sign (depreciation being lower with higher per capita incomes) and vehicles per capita having a positive sign (more used cars on the markets resulting in lower prices). The most likely explanation for these differing results is that income per capita is spuriously correlated with snowfall and salting. The North-Central, Mid-Atlantic and New England regions all have above average income and also have greater than average snowfall and use correspondingly more salt.

The reliability of the estimated coefficients for the salt use variables in the regression equation shown may be questioned on several grounds. First, some positive collinearity between salt use and snowfall is possible, which may imply that part of the variation of the depreciation rate associated with variations in snowfall is erroneously attributed to salt use. However, the relatively high t-statistics for the respective coefficients and the comparatively low correlation between salt and snowfall (.64 or less) suggest that this problem is not severe‡. Even so, it is difficult to answer this question with precision.

Second, relationships between environmental factors and automobile depreciation are confounded by the fact that cars are rarely exposed to one environment alone. Exposure of automobiles to different environments as the owners move or vacation is likely to reduce the variation in measured depreciation rates as compared to cases in which cars are less

* Generally, t-statistics greater than 2.0 indicate that the regression coefficient is significantly different from zero, i.e., that there exists a relationship between the dependent and independent variables.

+ Because of missing observations, three of the cases had to be excluded from the analysis.

‡ This comparatively low correlation may reflect the fact that many midwest and western communities rely on plowing and sanding for winter highway maintenance.

mobile. As a result, the regression coefficients estimated above may seriously understate the true relationships between independent and the dependent variables.

Third, the years chosen for the measurement of snowfall and salt use may not be representative. Consequently, fairly large errors in the measurement of the independent variables may be expected. Such errors can be shown to produce regression coefficients which are biased toward zero. In this case, the regression coefficients again would understate the true relationship.

Fourth, the analysis does not account for more recent improvements of design and corrosion resistance by manufacturers. Since most recent vintage automobiles were not included in the study, the estimates may overstate both the depreciation rates and their dependence on snowfall and salt use.

Given the data situation -- as well as the level of theoretical understanding of the problems involved -- the net effect of these factors on the reliability of the regression estimates cannot be determined with precision. All that can be done is to acknowledge these issues and take them into consideration in interpreting the findings reported here.

5.5.5 Estimation of Total Costs of Automobile Depreciation

The results of the regression analysis can be used to calculate the total economic costs of the incremental depreciation of automobiles attributable to the use of highway deicing salts. The procedure used for this purpose is straightforward: we need to determine the value of the stock of automobiles in various environments and multiply the stock value (by vintage) by the incremental depreciation attributable to salt use. Since adequate data on the composition of the total automobile stock by region and vintage are not available, data on the proportion of automobiles of each vintage still remaining registered (from R.L. Polk & Co.) have been used to translate total registrations into a total dollar value; Appendix B describes this procedure in greater detail.

Table 8 shows the results of these calculations. The first column contains the number of registrations by state, the next two columns show salt-use intensity, the fourth column displays the incremental depreciation computed on the basis of the regression estimates, and column 5 the incremental loss in the economic value of automobiles attributable to the effects of the use of deicing salts. This estimate is based on an average value per car of $1,500, as derived in Appendix B.

The total yearly national cost of the accelerated depreciation of automobiles due to the effects of deicing salts on corrosion is estimated at $1.4 billion, or $14 per car -- which corresponds roughly to 1% of the value of the average automobile. Since this measure is an overall average it is clear that the relative economic loss attributable to accelerated

Table 8

Cost of Automobile Depreciation

State	Estimated 1973 Registration (in thousands)	State Salt X .038	City Salt X .019	Depreciation X 100	Col. 1 X 4	Loss in Value X 1500, X 10 (in millions)
AL	1,837					
AK	109					
AZ	1,052					
AR	743	.1	2	.042	31	.46
CA	11,007	1	1	.057	627	9.41
CO	1,359	1.5	1	.076	103	1.54
CT	1,771	33	40	2.014	3,567	53.51
DE	284	12	25	.931	264	3.96
FL	4,358					
GA	2,538					
HI	413					
ID	412	1	.5	.048	20	.30
IL	5,095	19	60	1.862	9,487	142.31
IN	2,332	12	22	.874	2,038	30.57
IA	1,480	8.8	6	.448	663	9.95
KS	1,217	4.6	7	.308	406	6.09
KY	1,613	12	6	.570	919	13.79
LA	1,614					
ME	462	20	70	2.090	965	14.48
MD	1,938	30.9	33	1.801	3,488	52.32
MA	2,653	35	50	2.280	6,048	90.72
MI	4,414	29	100	3.002	13,242	198.63
MN	1,959	11	45	1.273	2,494	37.41
MS	963					
MO	2,077	15.1	25	1.049	2,178	32.67
MT	412	.1	1	.023	9	.14
NE	813	1.4	13	.300	244	3.66

Table 8 (Continued)

State	Estimated 1973 Registration (in thousands)	State Salt X .038	City Salt X .019	Depreciation X 100	Col. 1 X 4	Loss in Value X 1500, X 10 (in millions)
NV	318	.3	.3	.068	22	.33
NH	393	39	120	3.762	1,478	22.17
NJ	3,686	6	24	.684	2,521	37.82
NM	530	1	1	.057	30	.45
NY	6,360	18.7	50	1.661	10,558	158.37
NC	2,702	5	3	.247	667	10.01
ND	304	.4	1	.034	10	.15
OH	5,567	25.5	50	1.953	10,872	163.08
OK	1,377	.5	6	.133	183	2.75
OR	1,328	.1	1	.023	31	.47
PA	5,730	34	30	1.862	10,669	160.04
RI	500	35	25	1.805	903	13.55
SC	1,286					
SD	323	.2	2	.045	15	.23
TN	1,919	4.1	1	.175	336	5.04
TX	5,808	.7		.027	157	2.36
UT	565	39	8	1.634	923	13.85
VT	223	44	30	2.242	500	7.50
VA	2,329	10	20	.760	1,770	26.55
WA	1,786	3	2	.152	272	4.08
WV	704	25	20	1.330	936	14.04
WI	1,871	15.8	50	1.550	2,900	43.50
WY	183	.2	8	.60	29	.43
DC	222	27	15	1.311	304	4.56
	101,237			.917	92,879	1.392 Billion

automobile corrosion is substantially higher in regions affected by deicing salts. For example, for Massachusetts the estimate per automobile is over $34, or more than 2% of the value of the average car. It can therefore be concluded that the average annual loss attributable to the use of deicing salts varies between 1% and 2% of the value of the automobile.

In interpreting these figures, it should be remembered that the estimates obtained are based on the most conservative set of assumptions, as discussed above. For example, the estimated costs do not include additional expenditures on maintenance (such as more frequent trips to the car wash) or repair attributable to salt damage. Particularly the expenditures on undercoating would constitute a sizeable additional cost,* which is at least partially related to an attempt to reduce the effects of deicing salts. Cost data on the Ziebart rust-proofing process may be used to illustrate this aspect.

The Ziebart technique involves the application of a soft wax to steel surfaces in order to deny access to moisture, dirt, salts and soluble atmospheric pollutants. The present cost of this treatment ranges from $120 to $130, depending on the size and complexity of the car, with $130 a typical cost figure. Approximately 1.5 million automobiles have been treated by Ziebart since its incorporation.

Assume that the value of a car operated under ideal conditions depreciates at a constant exponential rate of 25% per year. The calculations in Appendix B show that Ziebart treatment then becomes economically justifiable if it prevents additional depreciation in the range of 1% to 1.5% per year (depending on the discount rate used). Since 1.5 million car owners have found it appropriate to pay for this treatment, it can be concluded that the incremental depreciation estimated above and presented in Table 6 is approximately in the correct range.

The costs of losses in economic value of passenger cars must be complemented by a rough estimate of the costs to trucks and buses. Although the present study has attempted to secure sufficient data for a statistical analysis of these costs, the data obtained provide little more than guidance for a relatively crude assessment. Based on information from truck fleet owners, incremental depreciation of buses and trucks as a result of corrosion is minimal, primarily because of greater efforts in terms of maintenance and treatments. The annual costs per vehicle have been estimated at $30 on the average on the basis of discussions with truck fleet owners and managers. For the 23,000,000 buses and trucks registered nationwide, the total annual costs of preventing salt-related corrosion damage would therefore be $690 million.

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* This cost is not necessarily an alternative to accelerated depreciation since the observed differences in depreciation rates occur in spite of differences in the relative emphasis on undercoating in different environments.

Under very conservative assumptions, the total annual cost of deicing salt use to owners of motor vehicles therefore is estimated here as being in excess of $2 billion.

5.6 OTHER DAMAGES

The review of damages attributed to deicing salts in the preceding sections has illustrated the broad variety by which salt runoff may alter natural environmental conditions, thereby initiating or aiding processes that result in real economic losses. By entering both the soil and the atmosphere, salt is contributing to a change in general environmental characteristics, primarily with respect to the ion balance, which affects patterns of corrosion and deterioration of materials exposed to these conditions. Consequently, damages that have been attributed to the use of deicing salts, have been noted in areas other than those discussed in the preceding sections. The available evidence on such "other" damages of course, is limited to reports on a few instances. However, a brief review of this evidence suggests that the potential effects of deicing salts on underground cables and electric utility lines may be substantial on a national scale.

One of the best-documented instances of salt-related damage to underground power transmission lines is the case of Con Edison's facilities in New York City. This company maintains in New York City the largest system of underground electric facilities in the world. The winters of 1972-73 and 1973-74 offered a striking contrast in terms of salt applications and in terms of resulting damages to this underground cable system. The winter of 1972-73 was comparatively mild, without much snow. The city used very little salt that year, about 20,000 tons, most of which was applied to bridges, ramps and critical intersections. In contrast, the winter of 1973-74 was characterized by two heavy snow storms leading to intensive salting; the city used about 120,000 tons that winter.

The effects of salt runoff on underground cables become evident almost immediately after application. These effects continue for two to three months as the salt brine is washed through the underground system. As a result, secondary cables (generally rubber-insulated and carrying 120 volts) develop short circuits resulting in fires. According to data furnished by Con Edison, there were approximately 1,400 more manhole fires in the winter of 1973-74 than in the preceding winter. These additional manhole fires necessitated extensive repairs and the replacement of almost 1,000 sections of secondary cable at a total cost of $4,000,000. In addition, there is evidence that the primary feeders (cables operating at 13,000 and 27,000 volts) are also affected by salt runoff from city streets. Since these cables are generally better insulated and protected, these effects develop more slowly.

In total, the company estimates that the salt spread on the streets of New York City resulted in additional expenditures by Con Edison in excess of $5,000,000 for the winter of 1973-74. This is a direct cost; added to it should of course be the costs of power outages to consumers, which are unknown. (The company has been lobbying for the adoption of other substances, such as magnesium sulphate, to replace salt at least on an experimental basis).

While this example constitutes an extreme case, it does suggest that the cost of damages to power transmission lines underground may be substantial on a national scale. In this particular case, the cost to Con Edison exceeded direct expenditures on the salt and its application by the city. Since these estimates do not include indirect costs to consumers nor damages to above-ground power transmission lines, it is reasonable to assume that the total national cost of these damages is at least double the cost for New York City, or $10 million a year.

5.7 THE DIRECT COSTS OF SALT APPLICATION

Before providing an estimate of the total costs of deicing salt use, it is necessary to estimate the actual costs to users of salt applied for snow and ice control. As mentioned above, salt use varies considerably from one winter to the next in response to snow and ice conditions. Therefore, the calculation of the annual direct costs of salt application refers to the annual average. (The annual figure must be an estimate of an average since supply conditions and transportation costs lead to sizeable variations in the price per ton of salt.)

Available data (307) suggest that the cost per ton of sodium chloride to users lies somewhere in the $10 - $20 range; the corresponding cost figure for calcium chloride is $30 - $35 per ton. In addition to these costs, the user also must account for the cost of application, which is about $5 - $10 per ton. Since the present annual salt use at the national level is approximately 9 million tons, the total annual costs can be estimated as about $200 million.

5.8 SUMMARY OF COSTS

The analysis in this section indicates that the actual costs of using salts for highway snow and ice control actually exceeds the direct costs of purchase and application by an order of magnitude. To recapitulate, the costs of the contamination of water supplies have been estimated at $150 million; those for vegetation at possibly $50 million, for cars at $2 billion, for bridge decks at $500 million, and for utilities as more than $10 million. Together with the cost of purchase and application, the use of deicing salts may cost the nation close to $3.0 billion.

The major share of this cost has been estimated for accelerated damages to vehicles, a case for which available data allowed for a direct application of the general cost estimation model. While it is somewhat speculative, it is reasonable to assume that other costs are likely to be higher. However, present data limitations do not allow for the exploration of the full range of these costs.

Since the available data allow only for illustrative estimates of the costs associated with different damage categories, a reasonable breakdown into direct and indirect costs to society and individuals is difficult. Since these breakdowns depend on institutional arrangements (cost sharing between society and individuals for certain damages) and actual practice (complete restoration may turn an indirect cost into a direct cost), on which only few observations exist, the best conclusions possible is that the major share of the cost is borne by the automobile owners (who, of course, also enjoy any benefits of bare pavement in the middle of winter). The remaining $1 billion are approximately evenly divided between individuals and society.

SECTION 6

BENEFITS OF ROAD SALTING

There are three benefits which have been ascribed to the use of salt for snow and ice removal: savings in terms of dollars, lives (safety), and time. The dollar savings is in terms of producing bare pavement in a given time under a constraint of a limited highway budget. As demonstrated in Section 5, the savings in snow removal from salt use cost that should be considered; indirect costs resulting from salt use are much higher than savings in snow removal costs. Consequently in terms of total direct dollar savings, (excluding safety and time savings for the moment), heavy salt use does not provide a cost savings, but instead incurs a net cost, and is therefore not a benefit.

On the other hand, salt is beneficial to the extent to which it increases safety and time savings. The relationship between salt use and these two factors is highly complex, especially with regard to safety. It is not within the scope of this project to perform an in-depth analysis of the functional relationship. However, it is appropriate to take a brief look at the work that has been done in these areas.

6.1 SALT AND SAFETY

The extent to which alternative winter maintenance policies affect highway safety is not established by the direct comparison of accident rates with maintenance policies unless driver behavior is explicitly incorporated as a parameter of the analysis. Although one would expect considerable research to have been directed toward understanding situations which involve the risk of injury and death, surprisingly little is actually known. Human behavior under conditions of financial uncertainty has a rich theoretical and applied literature, but such models are largely inappropriate for the analysis of accident risk, and attempts to model human behavior in situations involving the risk of life or limb have not been very successful. The existing evidence for a connection between safety and alternative winter maintenance policies is both meager and inconsistent.

It is often tacitly assumed that deicing salts improve driving conditions. Courts, in assessing liability for single-vehicle winter accidents, have found highway department officials negligent for not applying enough salt to provide an acceptable level of safety for motorists. Also, the assumed causal relationships between deicing salts and highway safety is a major rationale offered by highway department officials for the twenty-fold increase in the annual use of salts for highway deicing since 1950.

There is no question that salt can result in an increase in the coefficient of friction between the tire and road in most cases. Experiments have verified that under proper temperature conditions* the coefficient of friction for a snow covered pavement can be increased by the application of deicing salts (.05 kg. per square meter raises the coefficient of friction from 2.5 to over .40). (252) (In the same study sand, even when applied at ten times the rate, resulted in only a slight increase in the coefficient of friction on snow-covered pavement).

Three studies contain information which support the belief that deicing salts reduce highway accident rates during the winter months. One study was conducted by the city of Ann Arbor, Michigan. (258) In 1967, the last year before the use of salt for deicing became general practice in Ann Arbor, 315 accidents were reported; the accident toll fell to 196 and 186 during the next two years. However, because no information is available as to the number of winter storms, or other measures of severity of the winters, this data alone does not provide conclusive evidence.

The second study was done by the American Public Works Association (APWA) in Chicago during the winter of 1963-1964. (253) The APWA study contains numerous statistical tabulations of accident reports; for our purposes the most illuminating is the proportion of accidents which occurred on major and local streets under normal and adverse conditions. During periods of normal weather (dry roads), four-fifths of Chicago's winter highway accidents occurred on major roads. This percentage fell to two-thirds during periods when city-wide driving conditions were adversely affected by snow and ice, suggesting that winter maintenance, which is directed toward major streets, does improve highway safety. Although the data suggest that Chicago's chosen policy of maintenance, which relies heavily on salt for deicing, is effective, the accident reduction may be more dependent upon prompt plowing of major streets than it is on the use of salts for deicing.

The third study consisted of a survey conducted on salt use and effects in 116 U.S. cities during 1971-1972 (116 responses out of 504 requests (287). One of the findings of this study was given wide publicity and acclaim by salting proponents: "Salt deicing cuts accidents by 75% according to new 116-city survey." (259) However this statistic was based on responses from only 14 cities which were able to give a percentage breakdown of accidents in response to the question: "From these accident records, how many occurred on snow and ice-covered pavements against streets treated with deicing materials?" Furthermore, in response

* That is, in the temperature range in which salt melts snow and ice above -9°C for NaCl.

to the question, "Do your accident records show a relationship between weather and street conditions and damage to vehicles and/or personal injuries?", 42.2% of cities responded "yes", 40.6% responded "no", and 17.2% did not respond.

While the results of the study may be seriously questioned on the basis of the response sample, there are other serious research problems. First, the responses should be weighted by the percent of the salt treated areas in each city. Second, there was no backup in terms of snowfall. Third, the seriousness of accidents was unknown. Fourth, the extent of salt use on different types of streets was unknown. Fifth, the basis for information (accident records) is questionable, and probably not comparable between cities. Very honestly, all of these factors make the findings useless.

However, other studies have noted a potentially serious effect from the application of salt: invisible wetness. Salt in solution on a road has the effect of temporarily or indefinitely prolonging the drying of the surface, thus lowering tire friction. This situation is particularly dangerous because the road may appear dry. The greater the concentration of the salt solution, the longer the drying time. Higher air humidity will cause the salt to have a greater effect in delaying the drying rate. (254) In addition, under very low temperatures (-27°C for NaCl and -51°C for $CaCl_2$), too much salt decreases the melting rate and in some instances may assist the formation of ice (2). While these adverse conditions may occur only a very small fraction of the time, they still must be considered as a negative effect of salt. In a study of accidents in rural and urban cities within Oakland County, Michigan, it was found that as the use of salt increased, the percentage of accidents occurring under icy conditions decreased (249). This is to be expected since salt will reduce the frequency of icy conditions. However, it does not necessarily prove that salts increase safety, for the same study also found that the total number of winter accidents increased with increased use of salt. This apparent contradiction might be attributed to an increase in traffic as driving conditions improved, though this tentative conclusion remains unchecked because no statistics were recorded on vehicle density. The researchers commented that salting may create a false sense of security in many drivers (249). While this statement remains unproved, it is important to point out some analogous findings.

Two economists (Peltzman and Anderson) have noted that an improvement in safety, either in vehicles (automobile seat belts in the Peltzman study) or in highway conditions (Anderson), could elicit an increase in motorist's speed sufficient to render indeterminant the impact of safety improvements on accident rates (248, 257). Under hazardous winter conditions drivers do slow down, probably enough so that their perceived risk of injury is the same as under normal driving conditions (risk of minor accidents may rise or stay the same). Whether the perceived risk is the same as the actual risk is unknown. However, it is reported that an Ottawa, Canada consulting firm found from accident records that accidents occurring on icy roads are generally property damage, while accidents occurring on bare (dry or wet) pavement, during the winter are more likely to involve personal injury. (53)

Substantial research of the relationship between salt and safety is a necessity. While salt does serve to increase friction under proper use on a stretch of highway, this is not the only factor which determines accident rates. Research must consider continuity of conditions along a roadway, speed, and most of all, driver behavior. Such research will be extremely difficult indeed because determination of risk taking under varying driving conditions is a difficult (if not impossible) task. However, until such research is performed, it is false to assume that salt and safety are synonomous.

6.2 TIME SAVINGS

Anyone who has driven under snow and ice conditions knows that his progress is slowed, especially during rush hour. There have been scattered estimates of the cost of lost time (10), but there has been no major effort to assess the true value of the lost time. While the costs may be high, a certain amount of care must be taken in developing the figures. For example, it is false to suggest that a one hour delay for all persons in a city will result in a loss of one-eighth of the economic activity for that day. While there may be a one hour loss because of a shutdown of a continuous industrial process, there is probably little if any loss in terms of shopping expenditures. Shoppers will simply defer their errands to a later time with the result that there will be only a short-term loss to the stores. As a result of a survey on the impact of snowfall on manufacturing and retail activities in selected cities in the U.S., one study reported that:

> "Probably the most significant and best supported fact to emerge from the survey was the relatively small problem that snow appeared to pose for all types of manufacturing industry. Few, if any, of the firms interviewed felt seriously threatened by snow and the majority took only the most rudimentary precautions to ensure that operations were not disrupted. Also there was no conclusive evidence to support the contention that attitudes or actions were significantly altered by the actual snow environment" (Ref. 59, p. 110)

While this attitude may certainly be a result of the presently efficient snow removal procedures, it does seem to imply that a slightly increased delay in clearance of snow and ice would not produce disastrous results. Nevertheless, the question of actual cost of lost time from snowstorms is still a problem very open to research.

Better planning for the possibility of hazardous snowstorms would probably help to reduce business losses.

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APPENDIX A

GUIDELINES FOR ASSESSING ALTERNATIVES

The purpose of this appendix is to provide the reader with some very basic guidelines for evaluating alternative methods of snow and ice control. It is likely that many readers who are responsible for winter maintenance may have already performed equivalent evaluations many times before. However this appendix serves to point out some of the factors which must be considered in trying to reach a decision.

The foremost idea to be remembered is that the budget for winter maintenance is not the only constraint on the problem. The ideal solution would provide maximum safety and time savings while minimizing a total cost function. The total cost function would consist not only of the cost for snow removal, but also of the cost for vehicle, highway, utility, vegetation and water damage. However, as demonstrated in Sections 4 and 5, the development of a total cost function is impossible because of the difficulty in assigning costs to human health degradation from water pollution and to vegetation damage. Factors such as these may be used to impose additional constraints on the problem, rather than be included in a cost function. For example, to do this a community could impose the constraint that salt could not be used above a set amount on all highways within or bordering on a watershed area.

A second factor to consider is the requirement for bare pavement. Representatives of the community should help provide guidelines as to the importance of keeping various highways bare. Although there is certainly a time savings in keeping the highways bare, the link between bare pavement and safety has not been proven. Therefore, it is important to obtain input from the community on their concern for convenience versus their concern for the damage that results from salt. As pointed out earlier, under some circumstances the desired level of bare pavement may not be possible because of other constraints such as water pollution.

Once the level of bare pavement and all other constraints have been determined, the highway maintenance department should make an estimate of the probable reduction in salt use and the equivalent increase (if needed) in other activities to achieve the required level of bare pavements and to meet the other constraints. (Currently the safest activities to increase are plowing and sanding). The highway engineers should attempt to assess all local cost factors as well as possible (as has been done on a general level in Sections 4 and 5). Assuming that the effect of salt reduction is linear (a simple but not unreasonable assumption given the findings in Section 5), cost of salt damage for both the old and new situation can be estimated. As best as is possible, the cost analysis should consider the reduction in cost of damage to water supplies, vegetation, vehicles, highway structures, utilities, and any other elements unique to the community. This reduction should be compared to the possible increased cost of alternative snow removal procedures and the possible increased cost of loss time. All additional costs of the alternatives, such as other types of damage or spring clean-up of sand, must be included.

It is especially important that such an assessment be undertaken with the support and assistance of community representatives. In addition, if there are state highways passing through the town or if there is a water source within the town that supplies other communities, it will be necessary to bring state or other community representatives into the decision process so that all environmental factors can be included in the analysis. It should not be the sole responsibility of the highway department to make such a decision since the community has many subjective factors at stake, such as water quality, highway aesthetic value and property values, vehicle corrosion, and taxes for highway damage.

AN EXAMPLE

The following example is supplied to demonstrate how an assessment might be made as a practical matter. This example is in no way meant to represent a typical community situation, but the simple approach used should help pave the way for communities to perform their own analysis.

Let us examine for an entire winter season the case of a hypothetical town which has 20,000 families, a total population of 60,000, 25,000 vehicles, and 150 miles of two-lane highways. There are no state highways passing through the town and the town does not supply any water outside its borders. All of the water supplies are wells, both public and private. Approximately half of the vehicle corrosion damage from salt is attributable to the use of salt in the town (the remaining damage resulting from use of the vehicles outside the town.) Therefore, average vehicle damage from town salt has been set at $15 per vehicle. (see Section 5.4 for justification of a $30 cost per vehicle.)

Under the current winter policy, there is moderate to heavy use of salt, sand, and plowing. A majority of the wells in the town are showing dangerous levels of sodium, ranging from 30 to 100 mg/1, with the average level at 60 mg/1. The town has decided to undertake an evaluation of an alternative. The people of the town are concerned about their water and are willing to sacrifice some bare pavement to improve the water. The highway maintenance engineers feel that they can produce approximately the same level of bare pavement under most winter conditions (except possibly freezing rain or other special weather situations*) by tripling the plowing and increasing sand use fivefold in exchange for a 50% decrease in the salt use. The highway department and the community leaders have agreed to notify the community of the policy change through the news media and with prominent signs along the highways and at entry points into the town. Figure A-1 shows the comparison of the proposed Policy B to the current Policy A.

While Policy B shows a tremendous community savings over Policy A, it is important to note that any change that might occur in safety and time savings has not been accounted. These two factors are subjective in nature and they should be given careful evaluation by the highway engineers and community representatives. With proper public education and planning the importance of these factors can be minimized even if the same level of bare pavement cannot be maintained.

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* However, these conditions might even be handled by reserving heavy salt for the occasions and using even less salt under normal circumstances.

Table A-1

Cost Comparison of Two Snow Removal Policies

	Policy A	Policy A Cost	Policy B	Policy B Cost
Salt use per two-lane mile	20 tons		10 tons	
Total salt use	3,000 tons		1,500 tons	
Total applied salt cost @ $20 per ton		60,000		30,000
Plowing cost		50,000		150,000
Total sand use	2,000 tons		10,000 tons	
Total applied sand cost @ $4 per ton		8,000		40,000
Cost of clean-up of sand		5,000		25,000
Total Snow Removal Budget		$123,000		$245,000
Corrosion cost per vehicle attributed to salt used in town	$15		$7.50	
Total cost of vehicle corrosion		375,000		187,500
Damage to 5 bridges attributed to salt	$500 per bridge	2,500	$250 per bridge	1,250
Utility corrosion costs		500		250
Average Na^+ content of all water supplies	60 mg/l		30 mg/l	
Percent of population affected which should use bottled water*	5%		1%	

*While this cost may not be incurred directly, it is certainly less than the actual cost incurred in terms of health degradation.

Table A-1 (continued)

Cost Comparison of Two Snow Removal Policies

	Policy A Cost	Policy B Cost
Cost of bottled water at $.10/liter and 3 liters per day per person	328,500	65,700
Total Damage Cost	$706,500	$254,700
Total Cost to Community	$829,500	$499,700

Snow Removal Budget Increase	$122,000
Damage Cost Decrease	$451,800
Net Cost Savings to Community	$329,800

APPENDIX B

DEPRECIATION OF AUTOMOBILES

Previous economic studies of used-car prices indicate that a constant exponential decay model fits the data well*. Here some of the underlying causes of the depreciation of automobiles are examined and the separate contributions of certain factors including salts in the environment are estimated. We begin with a model of used-car pricing.

Ackerman has developed an economic model of used-car prices based upon widely accepted principles of capital theory. In her approach, the price of an automobile of a given vintage, K, can be expressed as the discounted present value of its remaining services.

$$(1) \qquad P(K) = \int_K^T S(x)\, e^{-r(x-K)}\, dx$$

where:
- K = present age of car
- T = age of scrappage
- x = age
- r = discount rate
- S(x) = services provided by car of age x
- P(K) = price of car of age K

Differentiation of equation (1) with respect to K yields equation (2)

$$(2) \qquad P'(K) = -S(K) + rP(K)$$

which indicates that the rate of price change for a car can be broken into two components, the flow of services and the opportunity cost of capital invested in the car. Equation two may be rearranged to obtain the service function:

$$(3) \qquad S(K) = -P'(K) + rP(K) \qquad \text{continuous time version}$$

or $$(3') \qquad S(K) = -\Delta P(K) + rP(K)/(1+r) \qquad \text{discrete time version}$$

* See studies by Ackerman (268), Bennett (272), Boiteux (273), Chow (276), Cramer (277), and Wykoff (296).

In order to estimate the service function it is necessarv to make some explicit assumptions about the time profile of services. Ackerman chose to model services as falling at a constant exponential rate with age.

(4) $S(x) = hP(O)e^{-ax}$

where: h = constant
$P(O)$ = price of car when new
a = constant rate of exponential decay of car services

substituting (4) in the expression for used-car prices, (1), one obtains

(5) $$P(K) = \int_K^T hP(O)e^{-ax}e^{-r(x-K)}dx$$

The price of cars of age K relative to the price of new cars is:

(6) $$P(K)/P(O) = he^{rk}\int_K^T e^{-(a+r)x}dx$$
$$= \left(\frac{-h}{a+R}\right)\left(e^{rK-(a+r)T} - e^{-aK}\right)$$

As T, the age of scrappage, approaches infinity this expression can be simplified since the value of $e^{rK-(a+r)T}$ will be zero in the limit. Thus:

(7) $P(K)/P(O) \approx Be^{-aK}$, where $B = \frac{h}{a+r}$

Equation (7) is the familiar result that used-car prices decline at a constant exponential rate. It may be estimated in the least squares format by converting to logarithms:

(8) $\ln P(K) - \ln P(O) = \ln B - aK$

For a given make and production year, one needs price statistics over a span of several years. Equation (8) is then estimated by least squares, the coefficient a is the estimate of the constant rate of decay.

AGE DISTRIBUTION OF CARS

The estimation of the total annual costs attributable to accelerated automobile depreciation because of deicing salts assumes an average car price of $1,500.

The $1,500 figure is obtained by taking the average new car price of $4,200 and a decay rate of 25% per year in price. The proportion of automobiles of each vintage still remaining registered can be obtained from R.L. Polk & Co data. It indicated the proportion of each vintage is as follows:

Age	Proportion
0 - 1	.08
1 - 2	.12
2 - 3	.11
3 - 4	.10
4 - 5	.09
5 - 6	.09
6 - 7	.08
7 - 8	.07
8 - 9	.06
9 - 10	.05
10 - 11	.05
11 - 12	.03
12 - 13	.02
13 - 14	.01
over 14	.04

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/2-76-105	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE AN ECONOMIC ANALYSIS OF THE ENVIRONMENTAL IMPACT OF HIGHWAY DEICING		5. REPORT DATE May 1976 (Issuing Date) 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Donald M. Murray Ulrich F. W. Ernst		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Abt Associates Inc. 55 Wheeler Street Cambridge, Massachusetts 02138		10. PROGRAM ELEMENT NO. 1BC611 11. CONTRACT/ NO. 68-03-0442
12. SPONSORING AGENCY NAME AND ADDRESS Municipal Environmental Research Laboratory Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268		13. TYPE OF REPORT AND PERIOD COVERED Final 8/74 to 7/75 14. SPONSORING AGENCY CODE EPA-ORD

15. SUPPLEMENTARY NOTES

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16. ABSTRACT

This study involves an analysis of the cost of damages that result from the use of salt (sodium chloride and calcium chloride) on highways to melt snow and ice. A large literature search and several surveys were carried out in order to determine the types and extent of damages that have occurred. The report contains over 320 references.

An in-depth analysis was performed on all of the data obtained. The major cost sectors examined were: Water supplies and health, vegetation, highway structures, vehicles, and utilities. For each of the sectors a cost estimate was developed. The total annual national cost of salt related damage approaches $3 billion dollars or about 15 times the annual national cost for salt purchase and application. While the largest costs result from damage to vehicles, the most serious damage seems to be the pollution of water supplies and the degradation of health which may result. It is particularly difficult to assign costs in this latter area and therefore the estimate may substantially understate the actual indirect costs to society.

These findings indicate that the level of salt use should be reduced. The amount of the reduction should be determined on the basis of local conditions.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Deicers Snowstorms Ice Control Economic Analysis Sodium Chlorides Water Pollution	Salt Stormwater Runoff Environmental Impact Snow Control	13B

18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 138
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

☆ U.S. GOVERNMENT PRINTING OFFICE: 1978— 757-140/6833