vandalism, obsolescence, and vibrations from traffic (American Public Works Association 1985).

Sidewalks and Driveways

Public and private sidewalks and driveways may be exposed to salt from direct application, splash and spray from traffic, pedestrian and vehicle tracking, and runoff from salt-laden snowbanks. If the concrete used is poorly finished or improperly air entrained, scaling may be accelerated by frequent exposure to salt (because of freeze-thaw effects). Most damage to sidewalks and driveways, however, stems from settlement, erosion, growth of vegetation, and traffic stress (American Public Works Association 1985).

Snow- and Ice-Control Equipment

Salt spreaders, hoppers, loaders, snowplows, blowers, and other equipment used for highway snow and ice control are susceptible to rusting because of road salt, especially if cleaning and maintenance are neglected. Because of differences in equipment usage and maintenance practices, the extent of salt damage varies by jurisdiction. As estimated in Chapter 2, nearly $500 million is spent annually by highway agencies to purchase, maintain, and operate snow- and ice-control equipment; hence, if even a small percentage is related to the effects of salt-induced corrosion, the total cost could be several million dollars per year.

Summary of Impacts on Other Highway Components

The durability of most highway components is affected by a number of factors, usually related to the quality of original construction, maintenance practices, and the environment in which they are located. Road salt is one of these factors, but not the most important. On the basis of the limited evidence available, the committee believes that, as a group, salt-related costs of damage to highway components are sizable but probably an order of magnitude smaller than bridge costs—totaling less than $100 million per year.

PARKING GARAGES

According to estimates from Census Bureau data, there are about 10,000 multilevel parking garages in the United States. About half are located in the salt-using regions of the Northeast and Midwest.[4] Although they vary in type from freestanding structures to multilevel decks integrated into other buildings, most are made of either cast-in-place or precast reinforced concrete. Many were built during the 1960s and 1970s, when concerns about salt-related corrosion were minimal. Most were originally designed for 40-year service lives without major deck repairs or renovation. During the past 20 years, however, hundreds have been deteriorating prematurely.

During the winter months, road salt is dropped by parked cars onto the slab flooring of parking garages. Over time, salt and moisture seep into the slabs, reach the reinforcing steel, and induce corrosion. The process is similar to that of bridge deck corrosion; the rust product expands and exerts pressure, causing the surrounding concrete to crack. The cracks allow more moisture, salt, and oxygen to reach the embedded steel, further accelerating the destructive process. Untreated, some of these cracks may expand to form delaminations that can lead to progressive structural weakening and losses in serviceability. In addition, leaky joints and poor drainage provide avenues for more salt and moisture, damaging walls, electrical conduits, and concrete beams and support columns.

Parking Garage Repair and Rehabilitation

Because of several decades of salting, hundreds of parking structures have had to undergo major repair and rehabilitation during the past 20 years. The most common method of repair is simple patching and surface sealing, which is often combined with waterproof membranes. This treatment may postpone the need for additional repairs for 2 to 6 years (Table 3-7). By the time numerous potholes appear, however, the garage deck is usually critically contaminated with salt, so continued corrosion and deterioration are inevitable unless more extensive repairs are made (American Concrete Institute 1985). Longer-lasting repairs usually involve removal of the unsound concrete, cleaning of the reinforcing steel, and placement of a modified concrete that reduces moisture penetration. This method of repair is about twice as expensive as simple patching but may postpone the need for more extensive repair by 10 years or more (Table 3-7).

TABLE 3-7 INCREMENTAL COST OF VARIOUS PARKING STRUCTURE REPAIRS (Tighe and Van Volkinburg 1989, 71)

Repair Option	Cost ($\$/ft^2$)	Added Structural Life (years)
Patching and sealing	1.00	2–5
Patching and membranes	3.25	4–6
Conventional concrete removal and replacement with high-performance overlay	7.50	10–12

Other methods of repair include cathodic protection and the injection of epoxy or other penetrants into cracks to serve as sealers.

Repair and Rehabilitation Costs

According to estimates derived from Census Bureau data, about 5,000 parking structures are located in the Northeast and Midwest (U.S. Department of Commerce 1989). Many of them, especially older ones built during the 1950s and 1960s, have already undergone major rehabilitation because of corrosion damage. Many newer structures built during the 1980s are equipped with state-of-the-art protections that should limit corrosion damage.

Although it is difficult to project how many of these 5,000 garages will be damaged by continued salting, the most likely candidates are those built during the 1970s. Many garages built during that decade lack protective systems and have not yet been restored. In recent years many have started to deteriorate. Information is not available on the number of parking garages in salt-using regions that were built during that period, although the committee estimates that the number is between 500 and 1,500 (about $\frac{1}{10}$ to $\frac{1}{3}$ of the 5,000 total garages in the Northeast and Midwest).

If an average of 1 in 10 of these structures becomes severely damaged each year during the next 10 years, 50 to 150 will need to be rehabilitated each year. The average cost of the most common method of rehabilitation—concrete removal, cleaning of rebars, and a high-performance overlay—is about $\$7.50/ft^2$ (Table 3-7). The average surface area of a parking garage is 150,000 ft^2 (500 stalls × 300 ft^2 per stall) (personal communication with consulting engineers, Elgard Corporation and Parking Market Research Company). Hence, the average cost of repairing one damaged parking structure is approximately \$1 million (\$7.50 × 150,000 ft^2), and the cost of repairing 50 to 150 per year is \$50 million to \$150 million.

Parking Garage Protection

In recent years, as corrosion damage has become more evident, most new parking garages have been built with structural features and protective systems intended to reduce chloride- and weather-related damage. About 90 percent of new structures are built with one or more protective systems (Table 3-8). Conventional methods—used in three-quarters of new structures—are penetrating sealers, membranes, and other surface treatments. Other methods include galvanized or epoxy-coated reinforcing steel, additional concrete cover, and corrosion-inhibiting concrete additives. In addition, more attention is paid to design and construction details, such as sloped floors for better drainage and proper concrete curing and finishing.

Protection Costs

According to estimates by the Parking Market Research Company (a reporting service for the parking garage construction industry), protective systems increase the cost of constructing a new parking garage by about 1 to 1.5 percent, or by about \$100,000 to \$150,000 per garage on the average (Parking Market Research Company 1987). Approximately 200 garages are built each year in the northeastern and midwestern United States, resulting in annual spending for protection of approximately \$25 million (200 × \$100,000 to \$150,000).

TABLE 3-8 TYPES OF WEATHER PROTECTION SYSTEMS USED IN NEW PARKING STRUCTURES (Parking Market Research Company 1987)

Protective System	Percent of New Structures[a]
Sealers, membranes, and other surface treatments	77
Coated reinforcing steel	13
Additional concrete cover	11
Corrosion-inhibiting concrete additives	7

[a] Column totals more than 100 percent because many structures have two or more protective systems.

UNDERGROUND OBJECTS

Corrosion damage to utility lines, pipelines, and steel storage tanks buried under or alongside highways is sometimes attributed to the use of road salt, especially in urban areas, which have a high density of underground utility lines and heavy salt usage. Altogether, the United States has about 2 million mi of natural gas and water distribution lines and service laterals (TRB 1988, 14). In many large cities electric and telephone distribution lines are buried underground; the total mileage of these systems is unknown.

Perhaps the best-publicized claims of salt damage to underground utilities have been made by Consolidated Edison Company of New York City. For more than 20 years it has blamed salt for occasional short circuits and burnouts of underground electric power transformers, switches, and service cables that are not well insulated (personal communication, Senior Research Engineer, Consolidated Edison Company; Murray and Ernst 1976). Apart from New York City, few occurrences of salt-related damage to underground utilities and pipelines have been reported. During the 1970s, the Illinois Bell Telephone Company reported corrosive failures of underground cables and transformers near where road salt was used (Kroon 1976). During the 1960s and more recently, higher-than-normal chloride concentrations in soils, possibly due to deicing salts, were identified as a possible cause of corrosion failures in some iron water mains in Milwaukee, Wisconsin (Hamman and Mantes 1966; Gummow 1984).

Utility industry associations contacted for this study reported few incidents of salt-related damage. The only problem reported by the American Gas Association was that road salt can aggravate corrosion of pipeline hangers and other anchoring hardware on bridge crossings (personal communication, Engineering Services Representative, American Gas Association). According to the Electric Power Research Institute, most buried electric distribution and service cables are well insulated, which reduces the likelihood of both short circuits (due to salt in water acting as an electrolyte) and corrosion damage. It was noted, however, that road salt may contribute to short-circuiting of older transformers, switches, and secondary lines that are not well insulated (personal communication, Engineering Representative, Electric Power Research Institute). The American Water Works Association did not know of any direct relationship between road salt and corrosion damage. It noted that road salt may be one of many factors contributing to a changing soil environment (e.g., higher chloride levels), which in recent years has caused many water companies to convert to corrosion-resistant materials for some pipe and valve components (e.g., stainless steel bolting on valves) (personal communication, American Water Works Association).

Finally, another potentially important, although uncertain, side effect of road salt concerns fuel storage tanks buried under gas station service yards. During the past 10 years in particular, the corrosion of these tanks has become a major environmental and public health concern. Thousands have been discovered leaking into surrounding soil, contaminating groundwater. According to the Steel Tank Institute, cleanup and removal of a single leaking tank can cost several hundred thousand dollars (personal communication, Steel Tank Institute). Because road salt is continually tracked into gas station service areas, it is considered one of many factors contributing to this problem, although it is not possible to isolate the specific effect.

The impact of road salt on underground objects, especially on a national basis, is difficult to quantify because of lack of information. Corrosion is second to excavation damage as the leading cause of failures in pipelines; pipeline operators and utility companies spend millions of dollars each year monitoring corrosion, installing cathodic protection, applying rustproof coatings, and repairing corrosion damage (TRB 1988). Expenditures on the cleanup and removal of corroding and leaking underground storage tanks amount to hundreds of millions of dollars each year (personal communication, Steel Tank Institute). Hence, although it is not possible to isolate the effects of road salt on these costs, even minor contributions could have major cost implications.

ROADSIDE OBJECTS

In addition to its potentially adverse effect on underground objects, road salt may negatively affect certain nonhighway objects located aboveground on the roadside. For instance, salt may contribute to the corrosion and degradation of bronze statues, monuments, and copper roofing that are exposed to traffic-generated splash, spray, and mist. The severity and extent of damage depend largely on prevailing local conditions, such as the degree of salt usage, the number of roadside objects, and the presence of other corrosion factors. Corrosion damage can be expensive and difficult to repair for many of these objects, especially those with historic or artistic significance. Available data are insufficient to isolate the effect of road salt on these costs.

SUMMARY OF COSTS

Great strides have been made in the past 10 years in reducing the adverse side effects of salting by protecting motor vehicles and infrastructure from corrosion. Advances are continuing, and the outlook for further reductions in damage is promising. Collectively, however, the indirect cost of salting remains high, because of both salt protection costs and persistent salt damages.

The committee's estimates of annual salt costs associated with motor vehicles and infrastructure are summarized in Table 3-9. The reliability of these estimates varies by cost item. Some cost items, such as motor vehicle protection and bridge deck damage, can be quantified reliably on the basis of available data (Category I). Summation of the more reliable cost estimates suggests a minimum indirect cost of salting between $2 billion and $4.5 billion per year. Several other cost items for which limited supporting data are avail-

TABLE 3-9 SUMMARY OF ANNUAL COSTS FOR MOTOR VEHICLES AND INFRASTRUCTURE FROM CONTINUED SALTING

Cost Item	Annual Cost ($ millions)
Category I (Data Reliable and Complete)	
Motor vehicle corrosion protection	1,900–3,900
Bridge decks	125–325
Parking structures	75–175
Total	2,100–4,400
Category II (Estimates Based on Committee Judgment)	
Motor vehicle corrosion damage	1,000–2,000[a]
Bridge nondeck components	125–325
Other highway components	100[b]
Total[c]	1,200–2,400
Category III (No Reliable Data Available)	
Roadside objects	N.A.
Underground objects	N.A.
Use costs[d]	N.A.

NOTE: N.A. = not available.

[a] From an illustration in Chapter 3 of the potential magnitude of these costs if car buyers in salt-using states are willing to spend an additional $125 to $250 per new car (the cost of existing salt protection) to eliminate persistent cosmetic corrosion.

[b] Cost totals less than $100 million, assuming it is an order of magnitude smaller than total bridge costs.

[c] Rounded to nearest $100 million.

[d] Examples include user costs associated with salt damage and repair to bridge decks and parking garages.

able, such as persistent motor vehicle corrosion and damage to highway components, can be approximated only on the basis of committee judgment and conjecture to provide a rough sense of scale (Category II). Inclusion of these items results in a less precise, although more complete, cost range of about \$3.5 billion to \$7 billion per year.

Because of lack of data, salt's additional impacts on bridge and parking garage users, underground utilities (and utility users), and other roadside objects cannot be similarly quantified. These costs are likely to be important in individual situations.

NOTES

1. As a method of approximating this cost, the committee initially considered comparing used-car prices in different regions of the country. Presumably, price depreciation is greatest in heavy salt-using regions, where cosmetic corrosion is more severe. For several reasons, however, the committee was not confident that this method of analysis would yield reliable results. For instance, factors besides corrosion can affect used-car price variations among regions, including differences in vehicle maintenance practices, driver skills, weather and driving conditions, and income levels. Also, used cars are often moved between regions for resale, which tends to reduce regional price differences. Because controlling for these factors would require a sensitive econometric model and wide range of information that is not readily available, the committee decided not to pursue this approach.
2. This approach requires surmising how much new-vehicle buyers would be willing to pay to prevent salt-related corrosion for the life of a new vehicle. Presumably, most new-vehicle buyers would be willing to spend at least as much on corrosion protection (at purchase) as the present-value cost of all future corrosion damage and preventive maintenance that would be avoided. Hence, by estimating "willingness-to-pay" for corrosion protection, the dollar cost of corrosion damage is determined implicitly.
3. Some treatments are available to counteract corrosion, but they are not widely used for various technical and economic reasons. One such treatment is cathodic protection, which can slow corrosion by providing a uniform current flow throughout the reinforcing steel. Cathodic protection is usually accomplished by impressing a direct electrical current between the reinforcing steel and an inert anode. Although cathodic protection has been used for years on buried steel pipelines, its use is less straightforward when applied to steel in concrete, which is inferior to soil as a conducting medium. Currently, only 200 to 300 bridge decks in the United States are cathodically protected (Swiat and Rog 1987).

   Another promising, although still experimental, treatment for controlling corrosion of contaminated decks is electrochemical chloride removal, in which a direct electrical current is impressed between the reinforcing steel and a temporary anode placed on the concrete surface. The impressed current, which is about 100 times' greater than the current used for cathodic protection, draws the chloride ions away from the reinforcing steel. Whereas the concept of electrochemical chloride removal is not new, recent work in Europe has led to successful techniques that are now being studied by several highway agencies as a possible concrete rehabilitation treatment for the future (Broomfield and Jawed 1990; Manning and Pianca 1991).

4. A precise count of the number of parking structures in the United States is not available. Parking garage construction consultants contacted for this study estimated that the number is close to 10,000 (personal communication, consulting engineers, Elgard Corporation). According to Census Bureau data, 3,145 parking structures were operated by private parking companies in 1987 (U.S. Department of Commerce 1989). This figure does not include parking structures operated by municipalities or institutions primarily engaged in other activities (e.g., hospitals and department stores). According to a survey conducted by the Parking Market Research Company, private parking companies accounted for about one-third of new parking garages built or planned between 1986 and 1989 (Parking Market Research Company 1987). If the 3,145 garages reported by the Census Bureau account for only one-third of all parking structures, the total number of structures is 9,435 (3,145 × 3), or roughly 10,000. According to Census Bureau data, approximately half of all parking structures—about 5,000—are located in the Northeast and Midwest, where road salt use is heaviest.

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ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
FHWA	Federal Highway Administration
MVMA	Motor Vehicle Manufacturers Association
NCHRP	National Cooperative Highway Research Program
SAE	Society of Automotive Engineers
SHRP	Strategic Highway Research Program
TRB	Transportation Research Board

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