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16. Abstract User costs related to maintenance operations represent a considerable amount of public expense in the United States. They are in the forms of extra fuel consumption, higher vehicular operating and maintenance costs, and additional travel time. As the demand for road maintenance keeps increasing, there is a tremendous need to reduce the user costs by introducing new technologies. Automating road maintenance can help to minimize the user costs. Fifteen automated systems for various road maintenance purposes are examined in this report that show very high potential in this regard. These developments not only represent a global trend of technological advancements in road maintenance, but also demonstrate that automation in road maintenance is technically feasible. An economic analysis which compares the costs and benefits of an automated crack-sealing system recently developed at Carnegie Mellon University and The University of Texas at Austin shows that such a system can reduce the direct costs of maintenance operations and produce numerous user benefits. With this economic analysis, it is clear that the automated systems will pay for themselves. One of the major findings in this study is that the greatest potential benefit represented by automation technologies in road maintenance is to reduce the user costs. The amount of money that can be potentially saved in this category is often much more than that which can be saved directly in maintenance operations.					
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**AUTOMATED MAINTENANCE TECHNOLOGY TO REDUCE FUEL
CONSUMPTION BY MINIMIZING LANE CLOSURE TIME**

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EXECUTIVE SUMMARY

From this study, it is found that tremendous needs for technological advancements exist in road maintenance. These needs include reducing the labor requirement of current maintenance practices as well as removing workers from potential danger and hazard, shortening the lane closure time by faster maintenance operations, minimizing the size of a work zone and the interference between maintenance crews and the traffic, increasing the capacity of maintenance forces to reduce the time lapse between defect formation and repair, extending the flexibility of maintenance forces in terms of working at night and under bad weather conditions, improving the quality of current maintenance techniques, and conforming to environmental regulations.

If these needs can be met by technological advancements, two major categories of costs directly or indirectly related to road maintenance can be reduced: (1) the direct costs of maintenance operations, and (2) the user costs. This study has focused specifically on automation technology as one major area of technological advancements in road maintenance. Fifteen automated systems in road maintenance are identified that are being used for defect surveys, traffic control, and defect treatment. These systems prove that automation technology is technically feasible and it can meet the needs for technological advancements in road maintenance.

The user benefits of automated road maintenance have been assessed in two major areas. In the possible reduction of the "action" costs, significant savings can be obtained by shortening the lane closure time and minimizing the size of a work zone. As illustrated in the examples, road users spend at least \$9.2 million (for 200 lane closures) annually in Texas on waiting, extra fuel consumption, and extra vehicle operating and maintenance expenses for passing work zones that contain crack sealing activities. If, with the introduction of the automated crack-sealing system, the operation time can be reduced by 10%, the immediate user benefits are close to \$1 million savings in Texas or tens of million dollars nationwide. Automating crack sealing will also result in operating benefits of several million dollars due to reduced labor requirements.

For "non-action" user costs, significant user benefits can be realized by shortening the time lapse between defect formation and repair. In the preliminary analysis of this study which assumes the International Roughness Index of a road will descend from 2.2 (good condition) to 8.8 (poor condition) after twenty years of service, it is calculated that road users spend \$83,921 annually in vehicular operating costs for each mile of driving on such roads. If we further assume

that out of all paved roads in Texas which totaled slightly more than 300,000 miles in 1990), there are 300 miles of roads in such conditions, the user costs in this category are \$25.2 million each year. This incurs even greater expenses than that of the "action" user costs.

Clearly, increasing the capacity of maintenance forces is a prerequisite to shorten the time lapse between defect formation and repair, provided that timely defect information can be reported by road surveys. With automated systems, there are fewer limitations on expanding the capacity of maintenance forces. The abilities of an automated system can be easily duplicated. With less human involvement, such systems can perform maintenance operations day and night and in most weather conditions. If, with automated systems, maintenance forces are able to expand their capacity and reduce the time lapse between defect formation and repair by 10%, user savings are in the range of two to three million dollars each year in Texas and tens of millions nation wide.

ABSTRACT

User costs related to maintenance operations represent a considerable amount of public expense in the United States. They are in the forms of extra fuel consumption, higher vehicular operating and maintenance costs, and additional travel time. As the demand for road maintenance keeps increasing, there is a tremendous need to reduce the user costs by introducing new technologies. Automating road maintenance can help to minimize the user costs. Fifteen automated systems for various road maintenance purposes are examined in this report that show very high potential in this regard. These developments not only represent a global trend of technological advancements in road maintenance, but also demonstrate that automation in road maintenance is technically feasible. An economic analysis which compares the costs and benefits of an automated crack-sealing system recently developed at Carnegie Mellon University and The University of Texas at Austin shows that such a system can reduce the direct costs of maintenance operations and produce numerous user benefits. With this economic analysis, it is clear that the automated systems will pay for themselves. One of the major findings in this study is that the greatest potential benefit represented by automation technologies in road maintenance is to reduce the user costs. The amount of money that can be potentially saved in this category is often much more than that can be saved directly in maintenance operations.

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CHAPTER 1 INTRODUCTION

In the United States, road maintenance consists of approximate 30% [1] of the total expenditures that are spent for road systems including the capital outlay of road construction, administration/miscellaneous, highway police and safety, etc. Table 1.1 shows the expenditures of national total and the State of Texas (excluding private organizations, airports and military) for road maintenance from 1981 to 1989. With the large amount of money involved, it is clear that road maintenance is a major category of governmental spending and requires careful consideration from various highway maintenance agencies as well as the public.

TABLE 1.1 TREND OF ROAD MAINTENANCE EXPENDITURES [1]
(National Total and Texas Total)

Year	National Total			Texas		
	Nat'l Total Highway Expen.	Nat'l Maint. Expenditures	% of Total (National)	Total HW Expen.	Texas Maint. Expenditure	% of Total (Texas)
1981	42,760,718	12,181,781	28.5%	3,151,270	801,351	25.4%
1982	43,292,915	13,319,148	30.8%	3,142,323	887,315	28.2%
1983	46,133,920	14,240,224	30.9%	3,293,686	875,498	26.6%
1984	50,680,308	15,008,437	29.6%	3,408,397	508,232	14.9%
1986	62,351,355	17,654,240	28.3%	5,218,341	1,048,683	20.1%
1988	68,590,116	19,109,804	27.9%	5,494,646	1,177,599	21.4%
1989	70,853,472	18,952,129	26.8%	5,496,521	1,130,841	20.6%

* 1985 and 1987 are excluded due to incomplete data

** All monetary values in thousand dollars

The considerations towards road maintenance can be placed on two levels. First of all, it is important to forecast the volume of road maintenance and to foresee and control, if possible, the factors that impose difficulties on maintenance agencies around states, cities, counties and other related organizations. If the demand for road maintenance increases, it is necessary to acquire more funding and to control the factors that create this higher demand.

Another level to be considered is when the demand increases, what should be the amount of additional funding and other resources that are needed to maintain the status quo of road serviceability or even improve it? If no additional resources are spent to keep up with the higher demand, road serviceability will suffer. This decrease of road serviceability will then increase the amount of user costs, such as vehicular maintenance, delays and accidents. Consequently, the amount of additional maintenance resources that is required should be

justified within the context where direct maintenance costs and user costs are both included in consideration.

1.1 HIGHER DEMAND FOR ROAD MAINTENANCE

The expansion of road systems during the period from the late 1960s to the late 1970s probably had the most profound impact on road maintenance difficulties for the past ten years and the years to come. During this period, an average of 19,500 miles of road were built each year. Due to the expansion, the day-to-day and scheduled road maintenance requires more resources. In other words, more funding is needed to maintain the expanding road systems

Because the majority of this country's roads were built more than twenty years ago, either before or during the expansion period, more and more reconstructions are needed as major road failures are frequently encountered and smaller-scale maintenance actions become less effective and more expensive. It is expected that this trend will not stop but continue until the end of this decade. As a result, the costly reconstruction may form a major category in road maintenance and issues around road reconstruction will attract more attention.

Along with the higher demands for small-scale maintenance and road reconstruction, one trend establishes another difficulty for road maintenance. This is the increase of the number of vehicles, including automobiles and trucks. The number of vehicles soars from 155 million in 1980 to 187 million in 1989, a 20% increase in ten years and more than 2 times that of population. A direct result of this is the increased usage of road systems, which subsequently contributes a higher volume of road maintenance.

1.2 PROBLEMS OF ROAD MAINTENANCE OPERATIONS

Road maintenance has been a labor-intensive industry and has only recently raised itself above the common-laborer level. Most of the current techniques regarding defect treatment as well as a number of supportive activities require much labor employment. In recent years, a major concern has changed the consideration regarding to the labor usage in road maintenance. That is the safety of maintenance crews. The runover accidents to maintenance crew caused by the inadvertent driving of the road users is not simply an increase of maintenance costs but a drastically negative factor to the overall success of maintenance activities.

In addition to the safety problem, the inflated costs of maintenance operation over time are significant. For instance, the average labor cost in 1989 is 158% of that in 1981, whereas the average inflation rate for the same ten-year period is approximate 36%. Similarly, the increase rates for other maintenance costs, such as material, equipment and overhead, are all more than that of the average inflation.

1.3 HIGH USER COSTS

When road defects are formed, every vehicular travel through the deteriorated road surface will cause some damages to the vehicle. As can be seen from the example presented in Chapter 3, the vehicle operating/maintenance costs can increase by 15 to 30% when the serviceability of a road decreases. If no immediate maintenance actions are taken to repair the defects, the user costs can easily go up to millions of dollars.

When road are completely or partially blocked by the work zone during maintenance operations, the traffic needs to either reduce its speeds or divert to another route. Either one of the cases causes road users delays and higher vehicle operating/maintenance costs. The user costs in this aspect can range from thousands to tens of thousand dollars daily. These costs increase even more dramatically as traffic is queued due to the lower speeds when approaching and passing through the work zone. The work zone which is set up to contain maintenance crews and equipment can also pose a potential hazard to the road users who misunderstand or fail to read signs. The property damage and bodily injuries are much more costly and sometimes difficult to measure.

1.4 OBJECTIVES OF THIS REPORT

In reaction to the problems that are faced in road maintenance, the main goal of this report is to examine the various possibilities of technological advancements in the road maintenance industry and to identify the opportunities of automating some maintenance activities in order to reduce both the direct road maintenance costs and the user costs. Specifically, there are four objectives in this report:

1. Review literature and statistics regarding problems in road maintenance,
2. Review literature regarding technological advancements and existing automated systems in road maintenance,
3. Investigate activities and automation opportunities in road maintenance, and
4. Examine the economic feasibility of technological advancements in road maintenance.

1.5 ORGANIZATION OF THIS REPORT

In Chapter 2, various characteristics of road maintenance activities will be identified and examined. First the definition and objectives of road maintenance will be introduced. Secondly, the six characteristics of maintenance activities that have been identified in this report will be discussed in depth individually. The needs of technological advancements in road maintenance will be examined in Chapter 3. In this chapter, two distinct view points, macro and micro views, regarding to the needs of road maintenance will be introduced. Also, the various cost aggregates and cost models that are related to road maintenance will be identified. Preliminary cost estimates regarding two aspects of users costs will be given in this chapter. The last section of this chapter will discuss strategies to minimize the costs of road maintenance in various aspects.

In Chapter 4, Opportunities of Technological Advancements in Road Maintenance, the core technologies of automation and the existing automation applications and developments to date in the areas of road defect survey, traffic control and defect treatment will be examined. Based on the preceding discussion, the potential benefits of technological advancements will be evaluated. Maintenance activities will be examined and divided into a number of elemental operations. The opportunities of technological advancements of five maintenance activities will be assessed.

In Chapter 5, the economical feasibility of technological advancements for road maintenance will be studied. An automated crack sealing system which was developed at Carnegie Mellon University will be included in the economic analysis. The costs and benefits of technological advancements will be predicted based on this study. In Chapter 6, the original objectives of this research will be reviewed and some conclusions will be drawn on future developments and research in the road maintenance industry.

CHAPTER 2 CHARACTERISTICS OF ROAD MAINTENANCE

The problems in road maintenance in the US have been briefly discussed in Chapter 1. To understand the background of these problems and the industry as a whole, it is necessary to examine the characteristics of road maintenance. First this chapter will provide the definition of road maintenance in Section 2.1. Three main objectives of road maintenance have been identified in this report and will be discussed in Section 2.2. After the background of road maintenance is provided, the last section will investigate the characteristics of maintenance activities in depth. These characteristics will later be used to examine the needs of technological advancements in this industry.

2.1 DEFINITION OF ROAD MAINTENANCE

According to the American Association of State Highway and Transportation Officials (AASHTO) [2], highway maintenance is defined as "a program to preserve and repair a system of roadways with its elements to its designed or accepted configuration." System elements include travelway surfaces, shoulders, roadsides, drainage facilities, bridges, tunnels, signs, markings, lighting fixtures, truck weighing and inspection facilities, etc. Traffic services and lighting and signal operations, snow and ice removal, and operation of roadside rest areas, movable span bridges should also be included in a maintenance program. Normally, the needs for road maintenance stem from the effects of weather, vegetation growth, deterioration, traffic wear, damage and vandalism. Deterioration includes the effects of aging, material failures, and design and construction faults.

With this broad definition, sometimes the boundaries between reconstruction and maintenance are blurred. However, in the context of this report, road maintenance refers to smaller-scale rehabilitation operations, usually less than 500 continuous feet, for travelways, auxiliaries and appurtenances. It also includes road defect surveys, since they may impact directly on user costs.

2.2 OBJECTIVES OF ROAD MAINTENANCE

The ultimate goal of road maintenance is to provide a safe and comfortable driving environment to prevent vibrations, loss of control and loss of traction upon driving. To accomplish this goal, three objectives must be achieved:

2.2.1. Restoring Skid Resistance

Road skid resistance is provided by the friction between the tire and two types of surface texture: the micro texture and the macro texture. Micro texture is the surface texture of the aggregate particles and the macro texture is the texture of the road surface. Micro texture is lost by the polishing effects of traffic, in particular by high volumes of heavy vehicles. On roads with bituminous surfaces, macro texture is affected by physical wear of the aggregate, aggregates being pressed into the surface, the bleeding of surface dressings. On cement concrete surfaces, macro texture is lost mainly by wear of the ridge. Another reason for the loss of road skid resistance is the accumulation of water on the road surface due to ineffective drainage. Since proper skid resistance is critical to the safety of driving, the restoration of skid resistance is one of the main objectives of road maintenance.

2.2.2. Restoring Road Evenness

The loss of road evenness is the result of the axle weights of vehicles that were applied to the road surface and other indirect factors such as the amount of travel, vehicle speeds, studded tire traffic, subgrade conditions, climate, original design and construction process. There is a wide range of road unevenness, such as bumps, indentations, waves, cracks, rutting, potholes, and loss of surface aggregates, that can cause the road users to experience minor vibrations to the loss of control. In some critical situations where driving safety is jeopardized, immediate maintenance actions are required. In less critical situations, proper effort should be made to defer the worsening of road surfaces.

2.2.3. Maintaining Road Impermeability

Moisture delivers a wide range of problems for road maintenance. It can reduce the interlocking mechanism between aggregates in the road base and the subgrade and cause a road to lose its bearing capacity. While moisture is in cracks, the freezing-thawing cycle and the drying process in high temperatures can severely damage a road's serviceability. While the presence of moisture is inevitable, effort should be made to seal all types of cracks and joint failures and to provide for the road systems an appropriate drainage system. While the permeability of road

surfaces does not pose any direct hazard or inconvenience to road users, it is an important cause for a wide range of road defects.

In addition, certain properties of road systems, such as visual effects of the surfacing such as glare, perception of road edges or obstacles, and noise affecting road users or residents, are becoming important and included as objectives of road maintenance.

2.3 CHARACTERISTICS OF MAINTENANCE ACTIVITIES

Road maintenance differs from road construction and any other construction activities in many aspects. These differences affect the design of maintenance equipment and techniques, the organization of maintenance crews, and the management of maintenance activities. Most importantly however, these differences affect user delay and fuel costs. A close examination of the characteristics of maintenance activities helps to clarify the technical advances necessary to reduce user costs due to maintenance activities. Seven characteristics have been identified and will be discussed in the following.

2.3.1 Small Scale Operation

Since road defects represent a very small portion of the total road areas, the resources such as labor, equipment, and material, that are involved in rehabilitating each defect or a section of defects are small. Because of this nature, two considerations have become significant and are well documented: the setup costs and the material and energy waste. While both of these costs impact the user indirectly, user delay and fuel consumption are also affected by frequent lane closure and excessive set up times. The setup costs of road maintenance are a function of the number of sections that require maintenance. When the size of each section is small, the total number of setups tends to be very large. While increasing the size of each section is not economically feasible because more energy and material will be wasted in areas where maintenance is not necessary, the obvious waste due to the frequent setups of equipment, work zones, etc., seems unavoidable.

In addition to the waste in frequent setups, more energy and material are wasted within the small-scale operations compared to those in larger-scale operations. For example, only a relatively small portion of the binding material, such as bituminous, for flexible pavements is used directly for filling cracks, whereas a larger portion is poured outside the cracks to be scraped off or

contained in the filling machine to be cleaned up. As a result, the small-scale operations tend to have higher unit costs than similar operations of larger scales do.

2.3.2 Dispersed Locations

Another characteristic of maintenance activities is that the locations of road defects are randomly spread throughout all road systems. The time spent on traveling between two sections of defect can sometime become the major part of the total maintenance time. Additionally, the mobility of maintenance equipment and the fuel consumed by its traveling are two importance considerations.

On the other hand, maintenance is often decentralized and is the responsibility of local organizational units (districts, townships, counties, etc.). The concentration of maintenance is often low: the work is spread over a wide area and has to be done piece by piece every year. This situation is not conducive to promoting the development of new maintenance equipment or to its acquisition.

2.3.3 Working Under Traffic

At times, maintenance crews have to work under traffic to repair certain types of critical defect. Not only does the work zone pose a tremendous inconvenience to the road users because of the lower speeds when approaching and passing through it, but also the traffic creates a number of difficulties to the maintenance crew. In this situation, the design of the work zone gets a great deal of attention. The considerations of work zone includes the setup of signs, barricades and protective facilities, the shape and size of work zone, and the direction of movement of work zone. A properly designed work zone can reduce the probability of road users' running into maintenance crew and minimize the productivity loss by the maintenance crew.

2.3.4 Labor-Intensiveness

At present time, the employment of labor in road maintenance is still intensive. This is partially due to the lack of technological advancements and the high costs of equipment purchase. In road surface defect surveys, raters are trained to record locations, types, patterns and severity of road defects while they are driving. Occasionally, they will slow down on stop and exit the vehicle for a closer inspection. Although some automatic systems are available, this type of task is mainly done by human raters. In traffic control, flagmen are often deployed to inform road users to reduce speeds or divert to a carriageway. After the operation is completed, flagmen have

to continue service until the curing process of the pavement material is ended. Almost without exception human workers are assigned to setup and remove the work zone and safety measures. In defect treatments, particularly of smaller scales, mechanized machines are seldom used.

2.3.5 Relatively Low-skill Level

By examining the operations that are involved in most maintenance activities, traffic control operations, and defect surveys, it is found that the required skills are relatively lower than those in road or other types of construction. While certain knowledge and training is required to obtain the desirable results, most operations tend to be either general-purpose or relatively low in complexity. The requirement of quality control is relatively low and the coordination and the interaction between different crafts are rarely seen.

2.3.6 Off-Peak Work Hours

When certain maintenance actions are needed, maintenance crews often manage to work during off-peak hours. The off-peak hours are defined as the time of a day during weekdays as well as weekends where the traffic is minimal. The occurrence and the total number of these hours vary from region to region and sometimes road to road. In some urban areas, these off-peak hours are few and the repair work that can be accomplished within these hours normally can not satisfy the demand for the day-to-day and the scheduled road maintenance. Overtime is sometimes used. However, the resulting higher labor costs and lower productivity are undesirable and difficult to resolve.

2.3.7 Affected by Weather Conditions

Undesirable weather conditions, such as rain, snow and extreme temperatures, accelerate the deterioration of road surfaces and sub-grades. In areas where severe weather conditions are frequently encountered, the demand for road maintenance is usually much higher. Because weather plays an important role in the causes of road deterioration, the demand for road maintenance usually fluctuates seasonally. In the peak seasons where the demand for road maintenance is the highest, the capacity of maintenance forces is often deficient. This deficiency can be either the lack of capacity to provide immediate actions as needed or the absence of knowledge to give proper treatment.

CHAPTER 3 TECHNOLOGICAL ADVANCEMENT NEEDS

Various approaches to resolving the problems in road maintenance have been proposed and implemented over the past years. Management techniques as well as some forecasting theories are commonly used to assess the demand of road maintenance, allocate maintenance resources, and schedule maintenance activities. New materials are being introduced to this industry to prolong the service life of repaired roads and to increase the efficiency of current maintenance techniques. Advanced quantitative techniques have been developed to evaluate the properties of the road system and to suggest appropriate actions to upgrade road serviceability.

The efforts in researching and developing maintenance equipment for the past twenty years are also extensive. Researchers studied the ways to increase the productivity of using loaders, graders, and other types of mechanized equipment to perform maintenance activities. However, the trend has been mainly focused on larger-scale operations and making use of conventional construction equipment. From examples in the construction industry, it is perceived that recent technological advances in automation provide tremendous potential for the road maintenance industry. Constant advancements in this direction will eventually resolve some of the fundamental problems in road maintenance. In this chapter, two views, macro and micro, regarding the needs of technological advancement in road maintenance will be discussed. Based on these two views, the potential user and tax payer benefits of technological advancement will be projected.

3.1 MACRO VIEW: THE TREND OF ROAD MAINTENANCE

This section will explore the causes of the problems in road maintenance, which have been briefly discussed in Chapter 2, and by using a number of statistics demonstrate the needs for technological advancement in road maintenance. The view point in this section is referred to as a macro view because it examines the historical background of road maintenance across states and analyzes the trends that affect the industry.

3.1.1 The Aging Road Systems

It is observed that the road systems in this country were rapidly expanded during the period from the late 1960s to the late 1970s. The summary of the total road mileage in this country for the past 25 years is presented in Figure 3.1. From this figure, it can be seen that during the 12-year period (1968 to 1979), this country's road systems surged from 3,684,000 to 3,918,000 miles, averaging 19,500 miles of increase each year. A considerable portion of them are multi-lane highway systems which are crucial for a larger volume of transportation but more expensive to maintain.

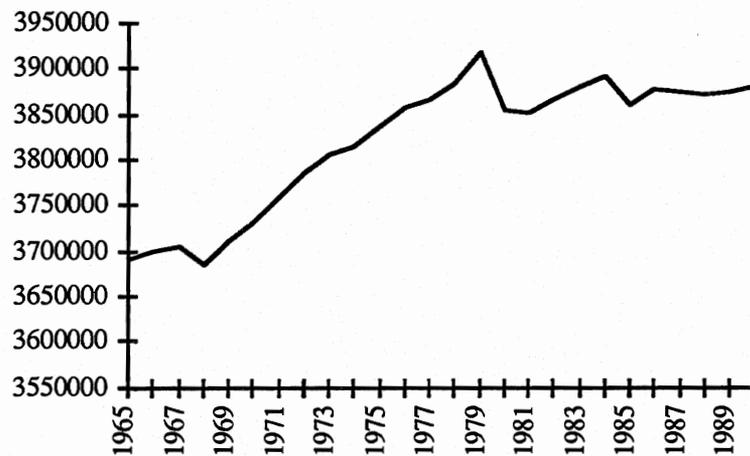


Figure 3.1 The Total Road Mileage in US from 1965 to 1990 [1]

While the trend of road expansion from the years 1980 to 1990 was relatively stable, the demand for funding in road maintenance is expected to increase for two main reasons: (1) the aging of road systems and (2) the difficulty to perform large scale road reconstruction. Usually the designed service life of road systems is about 25 years. When close to their service life, roads will show more and more major failures in terms of the total number and the frequency; at the same time, maintenance actions will become gradually less effective and more expensive.

Within the upcoming five years, the roads that were built during the rapidly expanded period will attain or surpass their service lives. This means more and more deteriorated roads will be encountered by the road maintenance forces and they will consume a larger portion of the available resources. If current maintenance techniques are still in use by then and the maintenance resources are not increased at the same pace, it is expected the overall

maintenance quality will suffer from the bigger demand of road maintenance. This trend is expected to last until the end of this decade.

A second issue involve the change regarding the relative importance between road construction and road maintenance. Although road systems should theoretically be renewed after their designed service life, a large-scale and overall reconstruction to replace the existing roads may not be feasible. Simply put, this will drastically affect the day-to-day traffic during construction periods and require a huge amount of funding to start with. The policy of post design-life road maintenance is therefore changed from focusing on large-scale reconstruction to a smaller-scale staged reconstruction.

Staged reconstruction, which builds or repairs a short section of a lane at a time, involves the intensive use of basic maintenance techniques such as patching, surface dressing, surface recycling and thin overlaying. As a result, along with the day-to-day and scheduled maintenance activities, more projects of road reconstruction will shift to staged reconstructions that employ the basic techniques of road maintenance rather than construction. The need for reducing road maintenance costs by enhancing the existing maintenance techniques and developing new ones is well perceived under these circumstances.

3.1.2 The Increase in Vehicular Travel

The population growth in this country has been maintained at slightly less than 1% per year for almost two decades. At about the same period of time, the increase of the total number of vehicles is much more significant than that of population [1]. Figure 3.2 shows this trend from 1980 to 1989. The growth of the number of trucks is averaged at 3% every year, which is three times that of the population growth. Also, the growth of automobiles is much higher than that of the population.

To better understand the relationship between the growth rates of vehicles and population, the ownership of vehicles per capita from 1980 to 1989 is presented in Table 3.1. From this table, it can be seen that the average ownership of automobiles and trucks is increasing: at present, less than two persons own an automobile (8% increase over the 10-year period) and less than six persons own a truck (19% increase over the 10-year period).

According to the above statistics, it can be inferred that the average vehicular travel in terms of the number of trips and the mileage of a trip is increasing. This increase can accelerate the deterioration of roads and broaden the impact of road closures on road users. When the deterioration of roads accelerates, more effort on road defect surveying and scheduled maintenance will be needed. In addition to the possible lower road serviceability, road users' complaints about the traffic jams, longer delays and the inconvenience of diverting traffic will surge. Not only are money and time wasted as a result, but the image of road maintenance agencies will suffer.

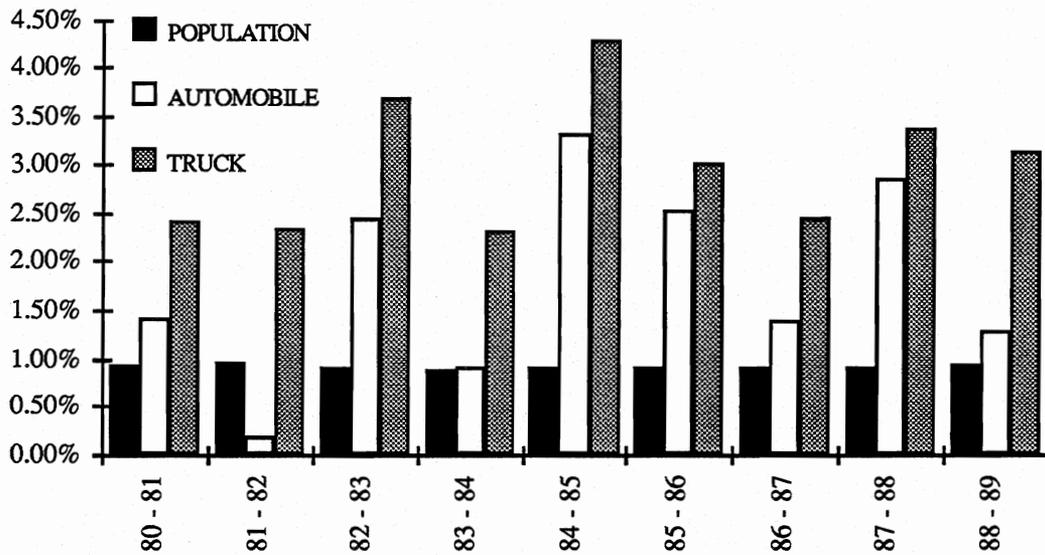


Figure 3.2 Percent Change of Population, Automobiles and Trucks [1]

TABLE 3.1 THE GROWTH OF OWNERSHIP ON AUTOMOBILES AND TRUCKS [1]

YEAR	POPULATION IN THOUSAND	AUTO OWNERSHIP	TRUCK OWNERSHIP
1980	227826	0.534	0.148
1981	229945	0.537	0.150
1982	232171	0.533	0.152
1983	234296	0.541	0.156
1984	236343	0.541	0.158
1985	238466	0.554	0.164
1986	240658	0.563	0.167
1987	242820	0.566	0.169
1988	245051	0.576	0.174
1989	247350	0.578	0.177

3.1.3 Stricter, More Extensive Environmental Regulations

According to environmental regulations, the pavement and sub-grade materials that are removed from repaired roads need to be disposed with some consideration. Since the volume of removed material and the travel distance to dispose of them are generally rather significant, the concept of recycling used material is gaining much attention. In addition, hazardous and solid waste amendments of 1984 represent a dramatic shift in national policy. Congress has mandated a redirection of waste disposal practices away from conventional land disposal methods and towards recycling, waste reduction and treatment. This trend poses a tremendous need for improvements of the current techniques. Table 3.2 shows the recent regulations regarding solid waste disposal.

TABLE 3.2 RECENT REGULATIONS OF SOLID WASTE DISPOSAL

Year	Regulations
1965	Solid Waste Disposal Act
1970	Presidential Order (Created EPA)
1976	Resource Conservation and Recovery Act (RCRA)
1976	Toxic Substances Control Act (TSCA)
1980	Comprehensive Environmental Response, Compensation and Liability Act (CERCLA): Superfund
1984	Amendments to RCRA
1986	Amendments to CERCLA

3.1.4 The Increasing Direct Costs of Maintenance Operations

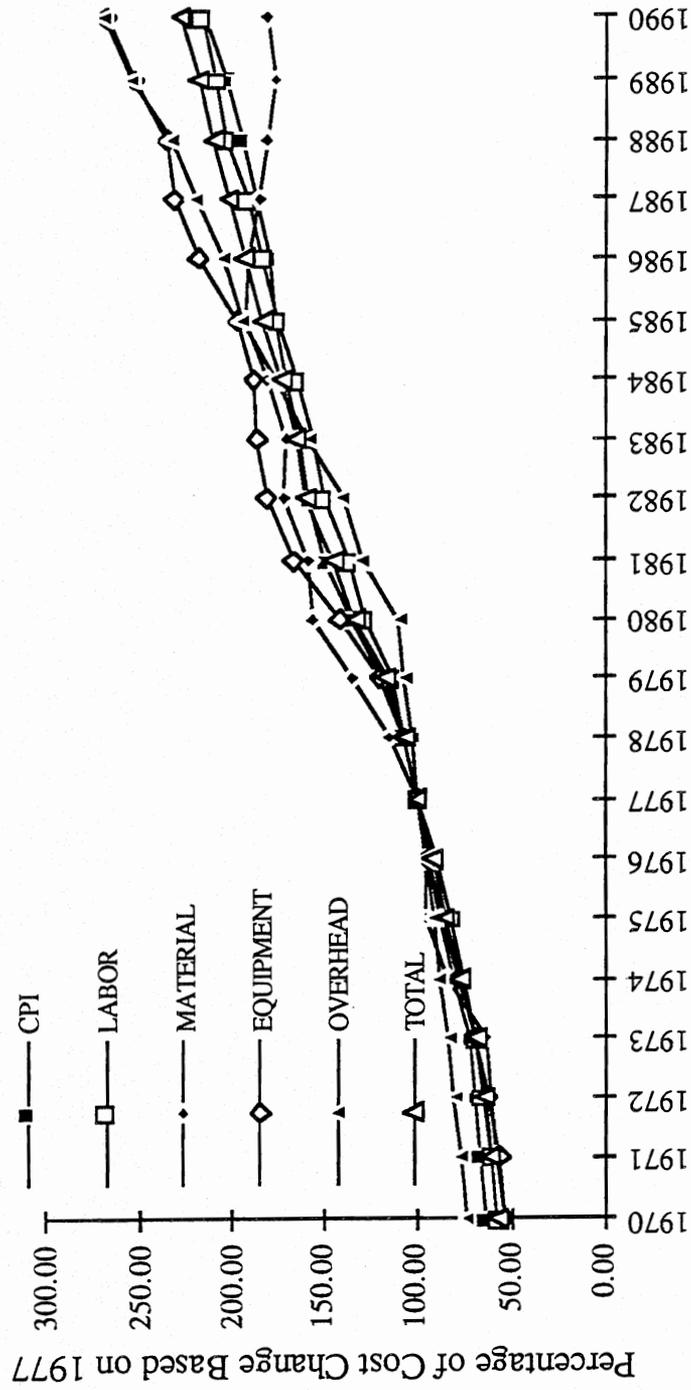
The direct costs of maintenance operation consists of four main items: labor, material, equipment and overhead. According to highway statistics [1], material costs normally form the largest cost item. This allocation of maintenance costs draws considerable attention to the possibility of reducing the material costs by recycling pavement material and introducing less expensive materials. On the other hand, the equipment costs as well as the overhead costs increased rapidly over the last several years compared to those of labor and material. In Figure 3.3, the cost trends for the four items, the total of them and the Consumer Price Index (CPI) from 1970 to 1990 are presented. Each point on the figure represents the costs of an item in a given year with respect to that in the base year, 1977. In other words, if the amount of money allocated to material in 1977 is \$100, then the cost allocated to material in 1990, which is approximately 180% to that of 1977, is around \$180.

The increasing costs of maintenance operations accompanied by the growing demand of road maintenance forms a difficult situation concerning whether the current maintenance practices can satisfy the various needs. Because it is difficult to control the demand of road maintenance, the problems in road maintenance have to be resolved by reducing the costs of maintenance and increasing the available resources. Strictly speaking, it is necessary to add funding at least proportional to the growth of maintenance demand. On the other hand, it may be as valid to focus on developments in maintenance techniques and materials that are essential to reduce maintenance costs, so that the same (or even smaller) amount of maintenance resources can service more roads.

3.2 MICRO VIEW: USER COSTS DUE TO ROAD DEFECTS

The context in this section is referred to as a micro view which turns the attention of road maintenance from a broader sense to a specific one. Having discussed the trend of road maintenance and the driving forces that make technological advancement in this industry a valid consideration, another dimension of observations is tied to the user costs that directly or indirectly result from road defects. These user costs are normally in the forms of travel delays, vehicular operating costs (including fuel consumption), vehicular maintenance costs and accident costs. Unlike the problems that are described in the macro view, user costs presented in this view normally can be controlled in some ways. Maintenance agencies often try to minimize the user costs and treat the reduction of user costs as an improvement of the overall maintenance service.

TABLE 3.3 COST TREND OF ROAD MAINTENANCE FROM 1970 TO 1990 (1977 = 100%)



The life cycle of a road can be represented by five distinct stages: construction, service without defects, service with defects, maintenance, and reconstruction. Two stages are of interest in this section: service with defects and maintenance. A breakdown structure of the user costs concerning the two stages is depicted in Figure 3.4. As can be seen from the figure, the user costs that result from maintenance operations (the upper half of the breakdown structure) are relatively easy to measure. The cost models to estimate user costs in this regard are found in several sources of literature [3, 4].

The user costs that are derived from the lack of maintenance action are more complex to measure due to the fact that the time lapse between a defect formation and repair is unknown in most cases. As well, the impact of a given defect on a specific type of vehicle is subject to different interpretations, not to mention the from one vehicle to another. Consequently, there is very little research and few proven cost models concerning the user costs of this sort. In this report, considerable effort will be placed on examining the variables of cost calculation, whereas the estimation of user costs will be based on the data collected from literature survey.

In Section 3.2.1, the user costs resulting from maintenance actions will be examined. Section 3.2.2 will focus on the user costs accumulated from the lack of maintenance actions. The following section will introduce a computer model called "QUEWZ" (Queue and User Cost Evaluation of Work Zones) [3] and briefly describe its algorithm and input/output data.

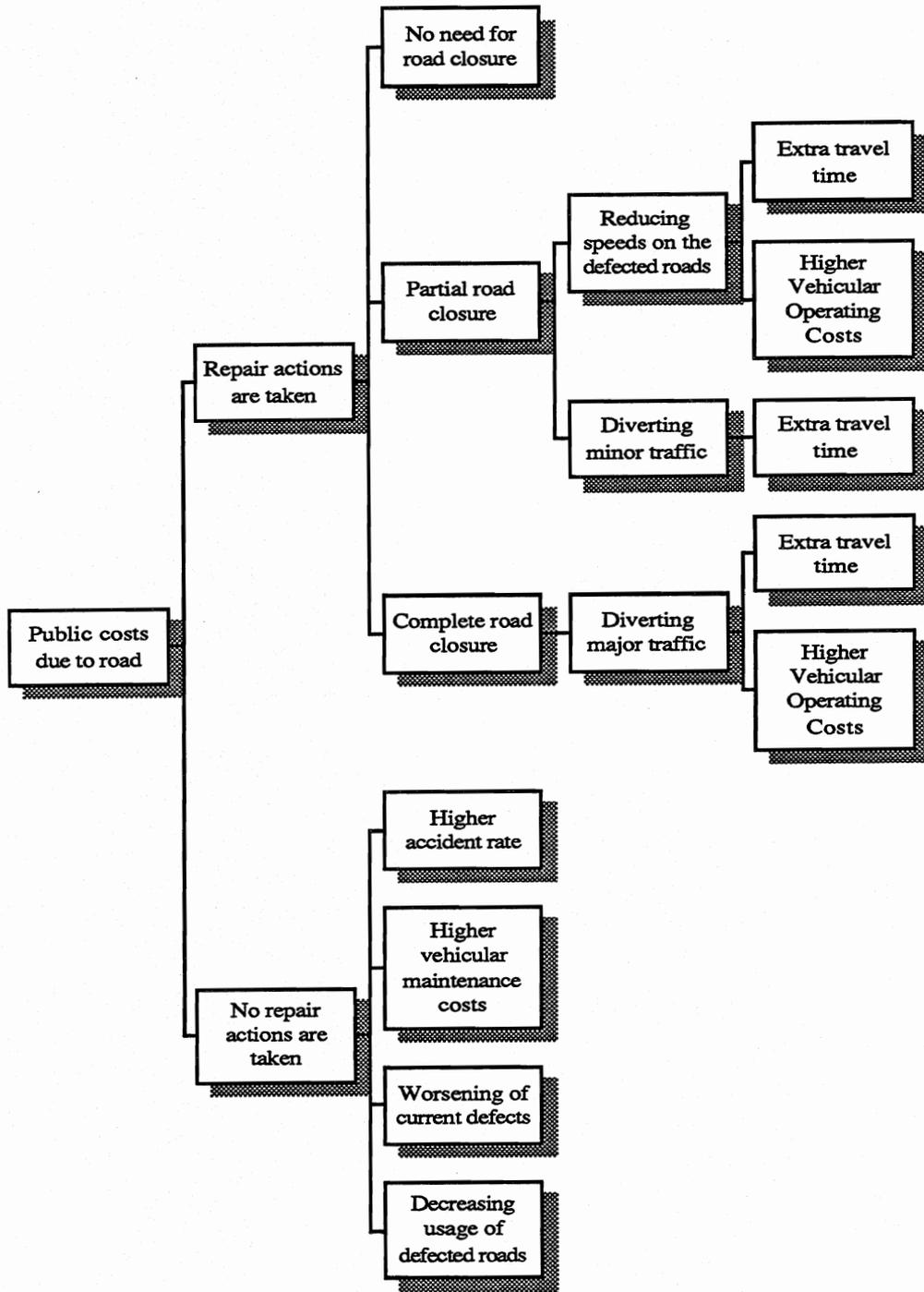


Figure 3.4 Cost Breakdown Structure of the User Costs in Road Maintenance

3.2.1 "Action" Costs

A. Costs of Extra Travel Time. The extra travel time is due to two main reasons: the lower average travel speeds and the longer travel distance. When a work zone completely blocks the defective road section, carriageways must be provided to connect the road to other temporary or existing roads prior to and after that section. If carriageways are not provided, the traffic will be forced to travel on other routes. In both cases, the extra travel time of each vehicle is due to the longer travel distance and can be calculated by dividing the extra travel distance by the average travel speed. Four variables that are also needed to compute the total user delay are (1) the actual hourly traffic that is affected by the road closure, (2) the time of lane closure, (3) maintenance activity and (4) the average extra travel distance.

If the defective road section is partially blocked, one or both directions of the traffic may have to reduce their speeds to comply with safety requirements imposed by maintenance crews. As a result, the travel time for that particular section is increased due to the slower traffic. To calculate the amount of delay, the length of closure (the size of work zone), the volume of traffic in each direction, the lane closure strategy, the total number of lanes, time of lane closure and maintenance activity, and the actual traffic by hour will need to be acquired either by field measurement or estimating.

Often, a third situation of delay happens when diverted traffic from the partially or completely blocked roads joins the adjacent routes. As the amount of traffic increases, the speeds of traffic tend to be slower. Even though the reasons for this kind of travel delay are straightforward, it is rather difficult to accurately estimate the amount. Factors such as the road conditions and the total volume of traffic including the existing and the diverted complicate the problem. In this report, this type of delay will not be included in the calculation of user costs.

B. Additional Vehicular Operating Costs. The additional vehicular operating costs can be divided into two categories: the costs due to extra travel and those due to waiting (stop-and-go cycles and lower average speeds). The first category is rather straightforward to calculate, in that it is a function of the extra travel distance, the average speeds and the vehicular characteristics. The second category involves two aspects: the operating costs of speed-change cycles and the change in vehicle operating costs due to the lower average speeds. The first aspect refers to the cost of slowing down and returning to the approach speed as a result of the presence of a work zone and the speed-change cycles in queuing. The second aspect deals with

the higher operating costs when the average travel speed is lower. Simply put, when a vehicle travels in a lower speed, the fuel consumption and the maintenance need tend to go higher.

To calculate the additional vehicular operating costs, a number of tabular data provided by the AASHTO Redbook can be used. Additionally, the variables already known in the calculation of travel delay, such as the length of closure, time of lane closure and maintenance activity and the actual traffic volume by hour will also be used.

C. Cost Model. A computer model, Queue and User Cost Evaluation of Work Zone (QUEWZ), developed to estimate the additional user costs resulting from lane closures in one or both directions of travel is described in [3]. User costs can be estimated when one or more lanes are closed in just one direction of travel or when a crossover is used. Hourly as well as daily user costs are estimated, and when vehicle demand exceeds capacity, the model also estimates the length of queue. The model is designed specifically for freeway conditions, but it can be used in other situations if appropriate adjustments are made in the input data. Two vehicle types are used in the model- passenger cars and trucks. The input and output data for this model are presented in Table 3.3. The algorithm of this model can also be found in [4].

TABLE 3.3 INPUT AND OUTPUT DATA OF QUEWZ MODEL [3]

1. Input Data
a. Required
(1) Lane-closure strategy
(2) Total number of lanes
(3) Number of open lanes through work zone
(4) Length of closure
(5) Time of lane closure and work-zone activity
(6) Actual traffic volumes by hour
b. Optional
(1) Factor to update cost calculations
(2) Percentage of trucks
(3) Speeds and volumes for speed-volume curve
(4) Capacity estimates risk reduction factor or work-zone capacity
(5) Problem description
2. Output data
a. Vehicle capacity
b. Average speed through work zone by hour
c. Hourly user costs
d. Daily user costs
e. Average length of queue each hour (if queue develops)

Many of the items in Table 3.3 are apparent. A few may need some explanation:

1. Currently QUEWZ handles two lane-closure strategies. The user is required to identify the time when lanes will be closed and reopened. For long-term road work that lasts for more than one day, the time of day when the work crews are at the site must also be specified.
2. The factor to update cost calculations is used to update the dollar user costs from December 1981 to current prices. The consumer price index can be used as the price index to update the user costs for inflation.
3. QUEWZ also allows the user to include a problem description. Such information as highway number, work-zone location, and so forth, can be included.
4. The program has constant values built into the model for all optional inputs. If the user does not specify values for the optional inputs, the program automatically uses its preset values. These program constant values, or default values, and details of the user cost calculations can be found in the Appendix.

TABLE 3.4 RESULTS OF SAMPLE PROBLEMS CALCULATED FROM QUEWZ [4]

Problem No.	Total No. of Lanes		No. of Open Lanes Through Work Zone		Length of Work Zone (miles)	Normal Capacity Each Direction (vph)	Restricted Capacity (vph)				Time of Restricted Capacity*		Longest Est. Queue Length (miles)		Total Additional Daily User Costs Due to Lane Closure (\$)	
	Inbound	Outbound	Inbound	Outbound			Work Zone Inactivity Hours		Work Zone Activity Hours		Begin	End	Inbound	Outbound		
							Inbound	Outbound	Inbound	Outbound						
1	2	2	1	2	1.0	4,000	1,800		1,332		1,332	8:00	4:00	1.9	0.0	17,647
2	2	2	1	1	1.0	4,000	1,800	1,800	1,332	1,332		8:00	4:00	1.9	3.0	38,211
3	2	2	1	2	1.0	4,000	1,800		1,332			**	**	1.9	0.0	35,923
4	2	2	1	1	1.0	4,000	1,800	1,800	1,332	1,332		**	**	1.9	3.8	83,756
5	3	3	2	3	1.0	6,000	3,600		2,983			8:00	4:00	0.0	0.0	546
6	3	3	1	3	1.0	6,000	1,800		1,127			8:00	4:00	3.6	0.0	64,108
7	3	3	2	3	1.0	6,000	3,600		2,983			**	**	0.0	0.0	847
8	3	3	1	3	1.0	6,000	1,800		1,127			**	**	4.1	0.0	120,878
9	4	4	4	3	1.0	8,000		5,400		4,577		**	**	0.0	0.0	368
10	4	4	4	2	1.0	8,000		3,600		2,968		**	**	0.0	0.0	986
11	4	4	4	1	1.0	8,000		1,800		1,200		**	**	0.0	3.2	101,485
12	5	5	4	5	1.0	10,000	7,200		6,200			**	**	0.0	0.0	214
13	5	5	3	5	1.0	10,000	5,400		4,500			**	**	0.0	0.0	436
14	5	5	2	5	1.0	10,000	3,800		2,745			**	**	0.0	0.0	1,126
15	5	5	1	5	1.0	10,000	1,800		1,200			**	**	1.7	0.0	81,736
16	6	6	5	6	1.0	12,000	9,000		7,900			9:00	3:00	0.0	0.0	64
17	6	6	4	6	1.0	12,000	7,200		6,200			9:00	3:00	0.0	0.0	113
18	6	6	3	6	1.0	12,000	5,400		4,500			9:00	3:00	0.0	0.0	217
19	6	6	2	6	1.0	12,000	3,600		2,800			9:00	3:00	0.0	0.0	551
20	6	6	1	6	1.0	12,000	1,800		1,200			9:00	3:00	1.8	0.0	27,495

* Work zone activity began at 9:00 a.m. and ended at 3:00 p.m.

** Closure for 24 hours.

Some sample problems have been calculated from this model by Memmott and Dudek [4]. Table 3.4 presents the summary results of 20 test problems. The same hourly traffic volumes are used for each problem. The freeway work zone is assumed to be 1 mile long and work activity begins at 9:00 a.m. and ends at 3:00 p.m. It is also assumed that the work zone remain closed for an entire 24-hr period for some problems, and for others it is assumed that closure begins at 8:00 a.m. and ends at 4:00 p.m. A vehicle mix of 8% trucks is also assumed.

By comparing Problems 1 to 4, it can be seen that two major factors dictate the amount of the additional user costs due to road/lane closure: the number of lanes closed and the periods of time during which the work zone exists and maintenance is in action. If assumed that in Texas, there are 200 road maintenance closures due to crack sealing in a year throughout the state of which 40% is of Case 1 and 20% of Cases 2, 3 and 4, the total user costs are approximately \$6.4 million based on the dollar in 1981 or \$9.2 million in 1990 (Consumer Price Index of 1990 = 143.8% of CPI of 1981). A large portion of these costs include fuel. According to the results of this example, the needs to facilitate the speed of maintenance operations and to minimize the size of work zones are apparent. For brevity of discussion, minimizing the number of lanes closed for maintenance activity is included in the calculation, whereas the sensitivity of minimizing the length of work zone was not discussed.

3.2.2 "Non-Action" Costs

A. Higher Vehicular Operating Costs. When no immediate maintenance actions are taken after a road defect is formed, every vehicle traveling across this defect will realize a certain level of damage. The level of damage depends on the type of vehicle, the travel speed, the type of defect, the type of road surface, and other minor factors. The additional vehicular operating costs for a single road defect are a function of the level of damage, the average maintenance costs of a specific type of vehicle, the time lapse between a defect formation and repair, and the amount of traffic per unit time. Although the additional operating costs of all vehicles passing through a given road defect can be calculated with reasonable accuracy, it consumes much effort and seems trivial to perform. An alternative way is to lump a section of a road into "one" defect and the rest of the calculation remains unchanged.

B. Costs of Accidents to the Road Users. When a road surface is deteriorated and no immediate maintenance actions are taken, three major classes of problems can result in driving accidents: the excessive vibrations, the loss of control, and the loss of traction. It is difficult to link any type of accident to a given road defect, because the causes of most accidents involve the driver's skills and perception, weather conditions, travel speeds, the surrounding traffic and other variables. It is safe to say that poor road serviceability promotes the probability of accidents. But it is difficult to give probability for estimation. So far, not much research has supported this argument with a sound statistical ground.

As well, it is difficult to estimate the average accident costs that are accrued to the road users. First of all, the causes of an accident that are not related to a particular road defect (or a section of road defect) have to be excluded from the accident costs calculation. Secondly, the items that should be included in the cost calculation are subject to a different definition of accident costs. These items include the damage to other drivers, the damage of personal belongings, mental damage of the driver and passengers, and the damage to public facilities. Third, after an isolated accident is obtained by excluding the unrelated causes and the irrelevant damage costs, measuring the accident costs is a highly subjective process. Normally, the cost calculation is based on the value of time spent on the accident, the hauling costs, the repair costs of damage properties, the medical bills and the costs of traffic delay to other road users.

C. Deterioration of the Existing Road Defects. After a road defect is formed, every vehicle crossing it will cause damage to itself as well as the defect. This deterioration process continues and can lead to a higher probability of accidents to road users and higher vehicular maintenance costs, so long as the defect is not repaired. To calculate the costs of deterioration of existing road defects, first the various stages and duration of defect deterioration need to be identified. Within each stage, the costs of accident and vehicular maintenance can be calculated as described previously.

D. Costs of Decreased Usage of the Defective Roads. As mentioned, road defects can cause some discomfort of driving such as vibrations, control difficulties and tracking problems. As the deterioration process of the defects continues, some road users may choose other routes to substitute for the deteriorated one. This problem is similar to the costs of delay described in the previous section. A major difference between the two problems is that the

amount of traffic that will divert to the adjacent routes is difficult to measure. An alternative way to acquire the volume of diverted traffic is to compare the values of three main variables.

The first variable is the conditions of the deteriorated road. This variable can be indexed by the number and the types of defect on the road. The second variable is the availability and conditions of the adjacent roads. This variable can be indexed by the distance between the alternative route and the deteriorated route, and the number and types of defects on the alternative route. Thirdly, there is a user preference whether to ignore the discomfort of driving or the inconvenience of using other routes. If these three variables are given an appropriate value based on the known conditions, it is then possible to estimate the volume of traffic that divert to other routes. The cost calculation is the same as that of the delay costs in Section 3.2.1.

E. Cost Model. A popular computerized model called "Highway Design and Maintenance Standards Model" (HDM-III) [5], issued in 1987, was developed by the World Bank to meet the needs of the highway community, particularly in developing countries, for evaluating policies, standards, and programs of road construction and maintenance. The original mainframe version of the model has been adapted to the personal computer environment and is available as HDM-PC, Version 2.0, which includes the core HDM-III model, a facility to input data, a facility to use the HDM outputs with Lotus, and a constrained version of the Expenditure Budgeting Model (EBM).

The model simulates total life-cycle conditions and costs and provides economic decision criteria for multiple road design and maintenance alternatives for one road link, a group of roads with similar characteristics, or an entire network of paved and unpaved roads. The primary cost set for the life-cycle analysis includes the costs of road construction and maintenance and vehicle operating costs, to which travel time costs can be added as an option. The costs of construction-related traffic delays, congestion, accidents, and environmental pollution can be entered in the model exogenously based on separate estimates. HDM-III can be coupled with the companion EBM to find the best way of using road agency funds under budget constraints.

As one of the primary interests of the report, one of the submodels of the HDM-PC, Vehicle Operating Costs, will be used to calculate the user costs due to the lack of maintenance action after defects are formed. A sample problem [5] will be presented in this section. In this example, it is assumed that an asphalt concrete road system is built in the year 1988. The vehicle

operating costs of five types of vehicles (cars, pickups, large cars, trucks and articulate trucks) will be calculated individually for the first year (1988) and the twentieth year (2007) after the construction. The International Roughness Index (IRI) will be used to represent the condition of roads. An IRI value of 2.0 means the road is in good condition and 9 means the road is in poor condition. A summary of calculated results is presented in Tables 3.5a and 3.5b.

TABLE 3.5A VEHICLE OPERATING COSTS FOR IRI = 2.2 IN THE YEAR OF 1988 [5]

1988 VOC ART. T	CAR	PICKUP		L. CAR	TRUCK
Ave. Speed (KM/H)	84.4	77.2	92.2	65.6	65.7
VOC per Vehicle-Trip	136.9	127.8	140.4	488.9	774.3
VOC per 1000 Vehicle-KM:					
Fuel	39.5	70.0	84.2	122.1	225.1
Lubricants	2.3	2.3	2.3	4.1	6.7
Tires	2.1	2.8	2.1	23.5	51.5
Spare Parts	6.4	13.4	13.8	43.4	133.2
Maintenance Labor	2.3	2.9	2.9	10.8	40.9
Crew	7.7	8.4	7.1	28.2	33.1
Depreciation	53.6	20.1	20.8	190.0	207.7
Interest	23.0	8.1	7.2	66.9	76.2

TABLE 3.5B VEHICLE OPERATING COSTS FOR IRI = 8.8 IN THE YEAR OF 2007 [5]

2007 VOC ART. T	CAR	PICKUP		L. CAR	TRUCK
Ave. Speed (KM/H)	74.2	66.5	78.6	53.1	46.1
VOC per Vehicle-Trip	157.4	165.0	181.5	615.6	937.1
VOC per 1000 Vehicle-KM:					
Fuel	41.9	73.8	91.7	122.9	247.3
Lubricants	3.4	3.4	3.4	5.3	7.8
Tires	3.6	4.8	3.6	26.1	58.1
Spare Parts	19.4	40.3	41.7	155.5	251.1
Maintenance Labor	4.2	5.2	5.2	20.9	56.8
Crew	8.8	9.8	8.3	34.8	47.1
Depreciation	53.1	19.7	20.4	183.6	192.8
Interest	23.0	8.1	7.2	66.9	76.2

Based on the results in Tables 3.5a and 3.5b, it is found that for every vehicle that has traveled through the deteriorated road the vehicle operating costs increase between 15% (Cars) to 30% (Large Cars). To calculate the user costs due to the lack of maintenance actions, the following assumptions are given:

1. The total length of roads of such conditions in the State of Texas is 300 miles.
2. The average daily traffic volumes are:

Car:	600
Pickup	400
Large Car:	400
Truck:	400
Articulated Truck:	300

Given all conditions specified in this context, it is calculated that the total user costs that incurred in a year (365 days) are \$83,921 per mile or \$25.2 million for 300 miles. It should be noted that the user costs in this example do not include the higher accident costs and the decreased road usage that are likely to happen when road conditions worsen.

3.3 STRATEGIES FOR ROAD MAINTENANCE

After examining the macro and micro views presented in the previous sections, several strategies for road maintenance can be established as an attempt to reduce direct maintenance costs and minimize user costs. The strategies are explained:

1. Develop new maintenance technologies (including methods, equipment and materials) to reduce the unit costs of maintenance operation. By so doing, the same amount of funding can have more impacts on upgrading road serviceability and reducing the user costs. Also, while the demand for road maintenance is growing rapidly, this strategy will lend itself to flexibility in managing road maintenance resources.
2. Once the road defects are reported, provide immediate maintenance actions, where possible. Since the user costs of the "Non-Action" stage heavily depend on the time lapse between the defect formation and repair, it is desirable to repair the defects as early as possible after they are formed. Although maintenance agencies are usually constrained by very limited resources, responsive maintenance actions, in many circumstance, will pay for themselves and deliver a good impression of maintenance agencies to road users. New maintenance technologies may enable quicker responses.

3. When a minor delay is possible or acceptable, avoid repairing during peak hours of traffic. It is found that road closures during maintenance operations create tremendous inconvenience and potential hazards to road users. Longer delays, especially where queues form, not only upset road users but also increase the vehicular operating costs and time of travel extensively. The stop-and-go cycles when a vehicle is approaching and passing through a work zone create a higher demand for vehicular maintenance. Accidents caused by work zones are very costly and should be eliminated as much as possible.
4. When repairing roads, minimize the size of a work zone to ensure the safety of road users and maintenance crews. Because it is not always possible to avoid traffic when repairing roads, it will be conducive for maintenance agencies to minimize the size of a work zone (both in terms of the number of lanes and the length of work zone). This strategy can help to reduce the length of waiting queues resulting from lower travel speeds and stop-and-go cycles and increase the restricted capacity while maintenance is in action. If the interference between the traffic and the maintenance crews can be minimized, not only the safety is improved but also the loss of productivity among crew members can be avoided.
5. Minimize the time that is needed for maintenance operations, including the repairing time and the curing time. From the perspective of road users, maintenance operations often mean much inconvenience. Road users' demand for a shorter operation time is apparent from examples shown. From the perspective of maintenance forces, a faster operation often means lower costs because labor and equipment costs are mainly determined by hours of service. As well, a more responsive service can be achieved because more road defects can be repaired by the same work unit for the same amount of time.

CHAPTER 4 OPPORTUNITIES FOR TECHNOLOGICAL ADVANCEMENTS IN ROAD MAINTENANCE

Having discussed the needs for technological advancements in road maintenance in Chapter 3, this chapter will focus on the *opportunities* for technological advancements. In this report, the main perspective for technological advancements will be placed on automation technologies. To begin with, the core technologies of automation will be examined in Section 4.1. In Section 4.2, the existing automation applications and developments in road maintenance in United States and other countries will be presented. Based on the experience learned from the existing automated systems, the potential benefits of technological advancements will be discussed in Section 4.3.

A thorough analysis of maintenance activities is included in Section 4.4, as a preliminary framework for the assessment of automation potential. In this section, 18 elemental operations are identified to cover the full spectrum of maintenance activities. In the section that follows, the automation potentials of five maintenance activities will be assessed in more detail.

4.1 CORE TECHNOLOGIES OF AUTOMATION

From examples in manufacturing, automation technologies have provided tremendous opportunities to upgrade the entire industry and fundamentally changed the base of competition. The following areas of technology constitute the core for development of automated road maintenance systems [6]:

A. Manipulators

Stationary, articulated manipulator arms are essential components of industrial robotics. The role of a manipulator arm is to move an effector tool into a proper location and orientation relative to a work object. To achieve sufficient dexterity, arms typically require six axes of motion (i.e., six degrees of freedom): three translational motions (right/left, forward/back, and up/down) and three rotational (pitch, roll, and yaw). Motion requirements of specific work tasks can be satisfied with various manipulator arm architectures. Movement of manipulator arms requires coordinated drive mechanisms to enable the execution of elementary motions with respect to each axis (or to each degree of freedom). Drive mechanisms used in robotics include hydraulic and air cylinders and electric motors. Special attention is given to precise speed control and extent of all possible motions. Accuracy and repeatability of manipulator motions depend directly

on the accuracy and repeatability of the drive mechanism. Drive motions are converted into appropriate speeds and directions of movement by transmission mechanisms.

B. End Effectors

A variety of end effectors can be employed on manipulators. Typical end-effector tools and devices on automated maintenance equipment include discharge nozzles, sprayers, scrapers, and sensors. The robot tools are usually modified in comparison with tools used by human workers or even specially designed to accommodate unique characteristics of the working machine. Integration of effectors, sensors, and control devices is possible to accomplish execution of more complex tasks.

C. Motion Systems

Mobility and locomotion are essential features for road maintenance equipment. A variety of mobile platforms can support stationary manipulators for performance of required tasks. An example selection of automatically guided vehicle (AGV) platforms is presented in Skibniewski [7]. However, most automated tasks supported by AGVs in road maintenance will require modified control systems and relatively larger payloads than in automated factories.

D. Controls

Controllers are hardware units designated to control and coordinate the position and motion of manipulator arms and effectors. A controller is always equipped with manipulator control software enabling an operator to record a sequence of manipulator motions and subsequently to play back these motions a desired number of times. More sophisticated controllers may plan entire sequences of motions and tool activations given a desired work task.

Computer-based controllers work at various levels of abstraction [8]. Actuator-level languages were the first to be developed and to include commands for movements of particular joints in a robot manipulator. These languages are cumbersome to use since a programmer must specify elementary movements and individual positions for each joint in the manipulator arm. At a higher level of abstraction, manipulator-level or end-effector level languages exist. These languages include commands specifying desired movements or positions of the end effector of a robot manipulator. When such a command is issued by an operator, the software must determine what actuator-level commands are required to achieve the desired final position. At the highest level of abstraction are object-level control systems and languages that can plan manipulator

movements in response to goal statements or sensor information. Knowledge-based expert systems may be used for this purpose.

E. Sensors

Sensors convert environmental conditions into electrical signals. An environmental condition might be a mechanical, optical, electrical, acoustic, magnetic, or other physical effect. These effects may occur with various levels of intensity and can be assessed quantitatively by more sophisticated sensors. These measurements are used to control robot movements and, in advanced robots, to plan operations.

Interpreting sensor information for the purpose of manipulator and end-effector control is a difficult and computationally intensive process. Consequently, most existing robots have only limited capabilities to sense the environment. As with control languages, different levels of interpretation exist. At the lowest level, mechanisms for receiving each sensor signal must be implemented, so sensor-level programs are required. Direct sensor measurements are converted into parameters describing the physical effect being considered. Finally, parameter values are integrated into a world model of the robot environment at the object level. Since different interpretation operations are very complex, smart sensors handling the calculation of parameters internally are gaining increasing attention. As a result, the robot controller does not devote time to polling and interpreting direct sensor signals. Since robots require real-time interpretation to guide robot actions, this form of parallel or distributed processing is highly desirable.

Artificial vision is an example of sensor and interpretation complexity. Vision is an information processing task in which two-dimensional arrays of brightness and/or color values received by a camera or other type of sensor are manipulated to form a two- or three-dimensional model of environment. This process may involve inferring the types of objects or material characteristics present in a scene with the use of complicated object-matching procedures. Area range scanners, now becoming available, will allow direct three-dimensional representations of the environment.

Integrating sensor information and machine control can be accomplished at various levels of abstraction. At the lowest level, tactile or proximity sensors may be added to a machine to stop any motions during imminent collisions. At higher levels, sensors provide the information required to construct a world model of a robot's surrounding. This world model is subsequently

used to plan robot motions to accomplish a desired goal. This overall integration distinguishes cognitive robots that are able to sense the environment, interpret data, plan, and execute work tasks.

4.2 EXISTING AUTOMATION APPLICATIONS AND DEVELOPMENTS IN ROAD MAINTENANCE

Having introduced the core technologies in automation, it is useful to describe briefly the key elements of the maintenance process, as a context for assessing opportunities and reviewing current automation applications. The four key elements and the current status of automation for each element are summarized in Table 4.1.

The third element, Maintenance Activities, is the primary focus of the report for two basic reasons: (1) most of the opportunities and potential for automation lie in this area, and (2) maintenance activities represent the major area of expenditures in the process. However, it should also be emphasized that an overall opportunity lies in the integration of data acquisition, processing and evaluation with the development of the automated procedures and equipment for actually carrying out maintenance work activities. In the following section, the state-of-the-art automation systems related to road maintenance will be presented. These new developments will be grouped into three categories: (1) road defect surveys, (2) traffic control, and (3) defect treatment.

TABLE 4.1 CURRENT AUTOMATION STATUS IN ROAD MAINTENANCE [9]

Key Elements	Current Automation Status
Data Acquisition, Processing and Evaluation (sectioning; acquisition of surface distress, traffic, environmental, and cost data; processing; assessment of current conditions)	Automated and semi-automated methods exist for surface distress data acquisition. Data processing and graphical/tabular portrayal of current conditions is highly automated.
Developments of Maintenance Programs (Setting standards; identifying deficient sections; determining most cost-effective treatments and schedules for sections; defining budget requirements)	Various computerized models or packages exist for developing maintenance programs and budget requirements (as part of a pavement management system)
Maintenance Activities A. Preventive Treatments • Crack routing and sealing • Surface treatments • Thin overlays B. Pavement Marking C. Corrective Treatments • Pothole patches • Crack repairs D. Traffic Control	Traffic control applications include a cone placement device, moveable barrier system, portable traffic signals and remote controlled follower vehicle. Maintenance treatment applications include surface and pothole patchers, a prototype robotic crack filler, automatic line painting systems and a multipurpose traveling vehicle for various maintenance tasks.
Post Maintenance Reporting and Evaluation (Maintenance quantities, locations and costs; comparison to performance standards and budgets; financial planning and program updates)	Processing and reporting of data on maintenance performed is generally a part of computerized maintenance systems.

4.2.1 Defect Survey

A. Automatic Pavement-Distress-Survey System. The Automatic Pavement-Distress-Survey System [10] developed by Komatsu Ltd., Japan, uses laser, video and image processing techniques to measure the three major types of pavement distress: cracking, rutting and longitudinal profile simultaneously without contact, rapidly and accurately. The data-processing system can convert the measured data automatically into formats that can be used in the pavement data bank. It was reported that cracks over 1 mm wide can be measured, and it is easy to output the various parameters calculated from length, width, direction, position and number of cracks. Another important feature of this system is that it can perform the survey at a speed of 60 km/hr or 37.5 mph.

While the vehicle is traveling, a road surface is illuminated with argon laser light that is scanned by a laser scanner in the transverse direction. The scattered light from a road surface is detected at an angle to incident direction by a photomultiplier tube (PMT) and a video camera in a front bumper. If there are cracks on the road surface, the quantity of received light of the PMT is reduced. A change of output from the PMT gives information about the existence of cracks at a scanning position. If there is unevenness such as rutting, the scanning line observed from an oblique angle is curved. The position of the scanning line in view of the video camera gives information about rutting. While the vehicle is traveling, the measurement on each laser scan is repeated, and then the distance is also recorded.

B. PASCO ROADRECON Systems. PASCO Corporation of Japan developed the first version of continuous pavement surface photographing device in the late 1960s [11, 12]. After a series of modifications, the current system makes measurements with two types of longitudinal profilers. One longitudinal profiler uses a tracking wheel, accelerometer, and differential transformer to measure the surface elevations in the outer wheel path. The other longitudinal profiler measured the distance between the vehicle body and the road surface using three infrared lasers, one in each wheel and the other in the center of the vehicle. This device is also used as an approximation of rut depth since each wheel path is measured.

Cracking, patching, and other distresses are recorded using a continuous road surface photographic recorder, called the ROADRECON-70 system. The vehicle travels at speeds between 3 and 53 mph (5 and 85 km/hr). A continuous photographic record of the pavement surface is made using a 35-mm slit camera. The system synchronizes film feed speed and camera aperture with the speed of the vehicle in order to equalize image density and photographic reduction. A continuous film record of approximately 37 miles of road can be created with 1000 feet of film. Road width up to 16 feet can be filmed.

C. GERPHO. The GERPHO (Groupe Examen Routier Photographique) System, developed in France by the French Ministere Des Transports, employs a survey vehicle to take continuous 35-mm photographs of the pavement surface [11, 13]. The system has been used extensively in France since 1972. It has also been used to a limited extent in several other countries, including Spain, Portugal, and Tunisia [14]. This system is similar to the PASCO ROADRECON that was discussed earlier.

The GERPHO system consists of a 35-mm continuously running (strip film) camera, mounted on a van with a light source that illuminates the pavement. The pavement surveys are conducted at night to allow for uniform lighting conditions. The film and light source are controlled as a function of vehicle speed. This system takes a continuous image of the pavement surface at speeds up to 40 mph. Between 63 to 125 lane miles can be photographed per working night. Two operators, who do not have to be highly skilled, are required.

The visual analysis of the negative films for distress data collection is done with a viewing table, and data storage and reduction is done with an operation station. The screen of the viewing table can show two rolls of films simultaneously, representing the equivalent of 65 feet with magnification of four. The distress data are directly entered into a microcomputer using a keyboard equipped with a special template of distress codes. The microcomputer, the special keyboard, a CRT, and a printer forms the operating station.

D. Automatic Road Analyzer (ARAN). The automatic Road Analyzer (ARAN) vehicle is produced by Highway Products International, Inc. of Paris, Ontario, Canada [11, 15]. It measures rut depth and transverse profile with ultrasonic sensors, ride/roughness quality with an accelerometer on the rear axis, takes a video picture of the road right-of-way through the windshield, takes a video picture of the pavement surface with a shuttered video camera behind the vehicle, and uses an on-board microprocessor to record distress data [16]. Seven ultrasonic sensors on 12-inch (30.5 mm) centers, mounted in a front-bumper rut bar, are reported by the manufacturer to measure the distance to the pavement surface with 1-mm precision at operating speeds up to 55 mph.

Additional sensors and bar extensions can be used to extend the rut bar to a width of 10, 11, or 12 feet. A calibration sensor is used to compensate for change in air density due to temperature variation. Microprocessor-controlled, plug-in optional keyboards, with built-in liquid crystal displays, automate the collection and recording process. Dual keyboards have the capacity to handle up to 20 distress categories in three severity categories and five degrees of area extent. Landmarks, such as bridges and railway crossings, can be recorded using eight special-event keys. The video equipment operates from a 12-volt power supply.

E. Laser Road Surface Tester (RST). The Laser Road Surface Tester (RST) was developed by the Swedish Road and Traffic Research Institute and has been used in Sweden for

more than six years [11, 17]. The RST can reportedly measure crack depths and widths, rut depths, longitudinal profile from which roughness is commuted, macrotexture, cross profile, and distance.

The device uses eleven bumper-mounted laser range finders and an accelerometer to measure the transverse road profile and detect cracks while traveling at speeds of 18 to 55 mph [11, 18]. A pulse transducer, mounted on the wheel hub, measures the distance traveled by the unit. Seven of the lasers pulse at 16 kHz and are used for the rut depth measurements. Four of the lasers pulse at 32 kHz and are used for macrotexture and longitudinal profile measurements. These lasers have a reported accuracy of 0.01 inch. An on-board microcomputer integrates the sensor signals with the accelerometer and distance transducer, averages the data into manageable sections, and provides the processed data in real time.

4.2.2 Traffic Control

A. Addco Cone. The "Cone Wheel" from Addco Manufacturing Company is a good example of how an improved mechanical device or process can increase productivity and safety [19]. The Cone Wheel is simply two large diameter, parallel wheels with a gap between them where traffic cones can be fed and retrieved by a worker.

The device attaches easily to either side of a pickup truck and can be quickly mounted and dismounted. The worker sits in the box of the truck to afford a measure of safety from on-coming traffic. The Cone Wheel also boosts productivity because the operation of placing or retrieving cones is performed much faster than by hand.

B. Quickchange Movable Barrier System. Originally developed in Australia, the Quickchange Movable Barrier System is now manufactured in the United States [20]. The system consists of a 10,000 ft. chain of 1,400 lb. hinged concrete sections and a machine to place and retrieve the barriers. The machine, which is controlled by two operators, lifts each barrier off the surface, transport it on a large conveyor belt, and accurately repositions the barrier on its new lane location. The entire operation takes 25 to 30 minutes to perform.

C. Super Quartz II Portable Traffic Signals. The SG II Portable Traffic System from Horizon Signal, makes it possible for highway crews to automatically control traffic flow by way of a series of microprocessor-controlled, battery-powered signals [21]. Up to 16 traffic lights can

be controlled from a single, user-programmed micro-terminal. The user-friendly system asks only the length of the work zone, the speed of traffic and the volume of flow. All calculations are performed internally and the system can begin operation immediately.

Once programmed, the SQ II system will continue to operate using one fully-charged 12 volt battery for a minimum of 72 hours, with an emergency 24-hour reserve available if required. Battery life is further extended because the system automatically adjusts the output voltage based on ambient light conditions.

The system has proved valuable for highway construction/repair operations, emergency traffic control, sports events and various other applications where temporary automatic traffic control is required.

D. Remote Controlled "Follower" Vehicle. Many serious accidents occur every year from motorists colliding with road construction crews as they work next to on-going traffic. Currently, the Minnesota Department of Transportation is developing a remotely controlled "follower" vehicle that can provide a buffer between the crews and the public [22].

The system consists of a large heavy truck (a dump truck for example) which can be operated from safe distance by a semi-skilled operator. The truck, follows the crew slowly (approximately 5 mph) and the operator can control the steering and speed of forward motion. The truck can be fitted with signs alerting the public, as well as cushions to lessen the damage from a collision.

While this does not qualify as "automation" in the true sense, it is a technologically advanced method of control and reduces a serious hazard to the workers. Furthermore, the system is only in the initial stages, and the potential for a greater degree of automation is definitely present. For example, it could borrow technology from the FASTNAV vehicle funded by DARPA and developed at Carnegie Mellon University which drives itself down the road [23].

4.2.3 Defect Treatment

A. Dynapac Pavement Patcher. Introduced in the mid 1980s, the Dynapac Pavement Patcher HR-21 was one of the first attempts to create a machine dedicated to this common maintenance practice [24]. The machine is a highly mobile unit that is towed by a large

truck (usually a tank truck carrying bituminous material), and is capable of spraying emulsion, spreading aggregate and compacting the mixture all in one pass.

System components include an on-board computerized control system, a binder pump, an adjustable spray bar, a self-loading aggregate hopper and three static roller drums. It can be adjusted to various widths from 0.3 m to 2.1 m in 0.3 increments, and any spray pattern can be achieved including multiple parallel patches.

Apart from the obvious time savings due to the faster operation of the machine, it can be helpful to invest in a dedicated machine because it leaves other equipment available to perform more important tasks.

B. Thermo-Patch Pothole Patcher. Pothole patching is a practice that has a high potential for automation because of the repetitive, and sometimes dangerous nature of the work. The Thermo-Patch Pothole Patcher is a piece of machinery dedicated to the task of patching potholes [25]. While the degree of automation is very low, the potential for further automation exists, and the benefits of the system come from the convenience of using a customized piece of equipment.

Traditionally, pothole patching has been performed using equipment designed for other purposes. This results in inefficiencies and wasted material because of the nature of the equipment. The Pothole Patcher brings several different components together and is properly sized to adequately perform the task without material waste.

C. "Puff" the Pothole Patcher. One Man Inc., a small company in New Mexico, has developed a self-contained, mobile pothole patching machine [26]. The machine can be driven to the site at highway speeds and upon arrival, a variety of traffic control warnings helps to ensure the safety of the operator and the public.

All pothole patching operations are performed by the operator from the safety and comfort of the cab. Robot-like arms extend from the front of the vehicle carrying all the necessary tools for a proper repair job. All required asphalt materials are carried on the machine in heated storage containers, and space is allotted for the storage of waste materials removed during repairs.

The company claims that operators require minimal training and few specialized skills to use the equipment. Furthermore, potholes can be patched at a very high rate because of the mobility of the machine. Patch quality has been found to be high because the use of heated materials provided the best possible bond with the existing asphalt.

D. Automatic Crack-Filling Robot. A greater degree of automation in highway maintenance has been achieved in a prototype automatic crack-sealing robot [27, 28, 29]. Unlike other machines that are simply customized to better perform a specific task, the crack-sealing robot contains an image processing system that scans the road surface for defects and discerns whether a defect is a crack or not. This discernment is performed by integrating a video-based raster scan image (two-dimensional) with a laser range sensor that supplies information about the third dimension. Apparent cracks that show no depth variation are assumed to be surface marks and are ignored by the system.

After mapping the cracks in the road surface, the machine develops a traversal pattern for the execution of the repair process. The repair process is performed by an x-y manipulator with three mounted tools: a heated air torch, a sealing wand and the infrared laser range sensor. The prototype machine uses compressed air and a hopper to simulate the first two devices. The robot is intended to be towed behind a truck for field production use and operated in a stop-start fashion. Future modifications may make it possible for operation to take place in a continuous mode.

E. Automatic Line Painting Systems. Currently, several projects are underway with the goal of automating the pavement line painting process to increase the speed and accuracy of the operation while decreasing the demands placed on the driver. The line painting operation is uniquely suited to automation because of the monotony involved and the precision required (two largely incompatible characteristics).

Work is being performed that will allow the lateral position of the paint guns to be automatically controlled, as well as the triggering of the guns themselves [30]. In order to accomplish these objectives, a line detection system in conjunction with a lateral positioning system is required.

F. Multipurpose Traveling Vehicle. Societe Nicholas of France has developed a multipurpose traveling vehicle used for a variety of maintenance tasks [31]. this large machine (6.5 Tonnes), is designed to accept various existing and future tools. Presently, the machine is being used for mowing grass around roadway curbs. Future plans for the vehicle include sowing, ditch excavation, road marking and cleaning, surface cutting, brushwood clearing and salt dispensing.

4.3 POTENTIAL BENEFITS OF TECHNOLOGICAL ADVANCEMENTS

Conceptually, technological advancements are to support the objectives and fundamental strategies of road maintenance. With the introduction of automation technologies, the potential benefits of the technological advancements are rather unique:

A. Reducing the interference between maintenance crew and traffic

When repairing roads under traffic is inevitable, the interference between crews and traffic has to be minimized to maintain crews' productivity and safety. Reducing the number of workers in the work zone is one way to minimize the interference. For instance, flagmen can be replaced by programmable devices that can provide vocal and graphical instructions to the traffic and alert any vehicle that is approaching with a high speed. Specialized automatic equipment can replace workers and eliminate the situations where they have to expose themselves directly to the traffic.

B. Enabling Maintenance Operations to Take Place at Night

The advantage of repairing roads at night is that the amount of traffic is minimal. Day-to-day and scheduled maintenance programs are much easier carried out because there are very few constraints posed by the traffic. Consequently, the number of accidents due to maintenance operations is reduced. Nevertheless, the limitations of working at night are the potentially lower productivity and quality of work. While it is possible to resolve these problems by providing proper lighting in the work zone, the huge amount of energy wasted and costs involved make this possibility slim. By using new technologies, such as infrared light and laser, it is possible to sense the conditions of a road defect without visible lighting. The information provided by the sensors can assist workers in repairing defects and inspecting the quality of work at night as well as day time.

C. Enabling Maintenance Operations to Take Place in Undesirable Weather Conditions

Under certain weather conditions, such as rainy days or extreme temperatures, many maintenance operations are difficult to perform. If forced to perform, the crews will have tremendous difficulties to maintain the quality and the durability of the repair. Simple sensors can be used to monitor the ambient temperature and the water content of the pavement materials, giving the information that crews need to make necessary adjustments. Other devices, such as fans and dryers, can be equipped with sensors and used to adjust the local work conditions and the pavement materials to comply with the quality requirements. When immediate maintenance actions are needed under undesirable weather conditions, these technologies can improve productivity and quality extensively.

D. Reducing the Direct Costs of Maintenance Operations

Most of the existing maintenance techniques rely on the intensive use of labor. This practice is becoming less desirable because of the increasing costs of labor wages, benefits and accident compensations. Also there may be an impending labor shortage, but most importantly, the highway departments are experiencing high turnover rates which make refraining more frequent, difficult and costly. New technologies can be used to replace workers or enhance their abilities, so that the unit cost of maintenance operations will be reduced. In highway construction, automated techniques have been used to perform physically exhaustive and repetitive tasks. In highway maintenance, a number of defect surveying techniques are used to facilitate the process of obtaining defect information. The automation concept should also be realized in maintenance activities.

E. Ensuring the Quality of work

Workers' experience plays an important role for the quality of maintenance operations. For instance, to fill a pothole, maintenance workers have to rely on their experience to determine what are the extent of loosened materials to be removed and whether the moisture inside the pothole will affect the quality and the durability of patch. If compressed air with a pressure sensor can be applied to clean a pothole, it will more precisely remove the materials that do not have proper interlocking or binding forces with other materials, while removing the moisture in the hole during the process. When spreading overlay materials, it is difficult to maintain a uniform thickness and a smooth curvature. By using sensors for feedback control, it is possible to assure the

thickness. Also, projecting transversal light beams across road surfaces can provide exact information about the curvature of the overlay.

F. Removing Workers from Direct Hazard and Danger

Exposing workers to the traffic during maintenance operations is a major drawback in most existing maintenance techniques. In many situations, work zones do not guarantee the full protection of crew members from careless drivers. With automation technology, workers in most situations no longer need to do their job manually. In the case of automated crack-sealing system introduced earlier, workers will control the system and monitor the progress inside the vehicle. Also, they can be away from the volatile organics that can cause dermatoses and respiratory problems. The improvement of workers' safety and health by technological advancements is apparent.

4.4 BREAKDOWN OF MAINTENANCE ACTIVITIES

As mentioned in Section 4.2, there are four key elements in the entire maintenance process. This section will focus on the third element, Maintenance Activities, and examine the task breakdown structure, in preparation for the assessment of automation opportunities in road maintenance. Depending on the objectives of road maintenance, there are three groups of maintenance activities that occur in day to day practices. The content and characteristics of these maintenance activities can be illustrated as follows:

A. Restore Evenness

The first group of maintenance activities is to restore the evenness of a defective road surface. These activities include: patching, surface dressing, thin overlaying, planing, trash removal and snow removal. These types of activity usually deal with a very small portion of a road and requires relatively low level of energy .

B. Maintain Impermeability

The second group is to maintain the impermeability of a road surface. These activities include: sealing, grouting, surface dressing, and thin overlays. Since cracks usually do not pose an imminent hazard to road users, these types of activities are usually performed upon roads with high speed limits or a huge traffic volume and are combined with other maintenance activities.

C. Restore Skid Resistance

The third group is to restore the skid resistance of a road surface. These activities include: (1) for rigid surfaces only, bush hammering, milling and sandblasting, (2) for both rigid and flexible surfaces, grooving, planing, surface dressing and slurry dressing. These types of activities usually deal with a large portion of a road surface and requires the rather extensive use of highly mechanized equipment. The scale of operation is large and the energy requirement is high.

Based on the maintenance activities illustrated above, it is found that a total of eighteen elemental operations can cover the full spectrum of all maintenance activities [32]:

1. Set up or remove work zone materials and traffic controls.
2. Identify, locate, detect or delineate areas of deteriorated material to be removed.
3. Cut, grind, mill, plane, or break deck or pavement materials.
4. Remove broken or disintegrated deck, pavement, or base material.
5. Clean, dry, and prepare patch area or surface area.
6. Prepare and place forms, screeds, or other material-controlling devices.
7. Apply tack coats or bonding material.
8. Mix and place patching, surfacing, or sealing materials.
9. Compact, vibrate, screed, surfacing, or finish patching materials.
10. Apply curing or blotting material.
11. Construct temporary travel surface over repaired area.
12. Clean out joint or crack.
13. Fill joint or crack.
14. Locate, layout, drill, and prepare mudjack holes.
15. Prepare slurry and perform mudjacking.
16. Apply liquid coating to surface.
17. Spread aggregate on surface.
18. Remove or pick up alien objects from road surfaces.

These elemental operations are useful in providing insight to maintenance activities. As can be seen in the next section, labor and machine utilization can be examined easily when a maintenance activity is in elemental form. The utilization of labor and machines can then lead to further discussion regarding problems such as safety of operation, speed of operation, superhuman handling, etc.

4.5 OPPORTUNITY ASSESSMENT FOR MAINTENANCE ACTIVITIES

This section will examine the opportunities for five maintenance activities: planing, patching, sealing, surface dressing and thin overlays. These activities are selected because they are commonly used for most types of road defects. The discussion of each activity will start from the identification of the elemental operations involved. In a tabular form, the crew size and organization and the equipment employed by the current maintenance techniques will be presented. Then, based on the identified elemental operations and the current practices, each activity's opportunity as well as the respective benefits for technological advancement will be assessed.

A. Planning

Three elemental operations are identified in a planing activity [33]: (1) identifying and delineating uneven road surfaces, (2) planing road surfaces and (3) cleaning road surfaces. By examining Table 4.2, it can be seen that most of the elemental operations are performed by machines or mechanized power. The only operation for both techniques that is completely done by human workers is to identify or delineate the uneven road surfaces right before any operation. In the case of heater planing, sweepers or shovellers are employed to clean road surfaces as normally power brooms can not remove viscous materials very well.

TABLE 4.2 CREW SIZE AND EQUIPMENT FOR A PLANING ACTIVITY [33]

	Cold Planing	Heater Planing
Crew Size	1 to 3 Drivers 1 Planer Opr. 1 Broom Opr. 1 Loader Opr. 1 to 3 Flagmen (Traffic Control)	1 Driver 1 Planer Opr. 1 Roller Opr. 1 Loader Opr. 2 Sweepers/Shovellers 1 to 3 Flagmen (Traffic Control)
Equipment	1 Crew Carrier 1 to 3 Dump Trucks 1 Self Prop. Cold Planer 1 Power Broom 1 Loader	1 Crew Carrier 1 Dump Truck 1 Heater Planer 1 Steel Wheel Roller 1 Loader

The opportunity to automate the identification of uneven surfaces is not very high simply because patterns and ranges of unevenness vary widely and the efforts and costs of collecting, storing, processing and manipulating image information are much higher when methods other

than human labor are used. However, one essential possibility to facilitate the entire activity is to collect, store and process surface information by men and to manipulate the processed surface information by computerized methods. This requires certain technologies that can transform human's thoughts into digital data in real time. If this can be achieved, planing machines can make use of the processed information to execute the needed functions and adjustments without the intervention of the operator.

In addition to the employment of human workers, this activity involves the use of three types of machines: planers, power brooms/rollers and loaders. One highly undesirable situation resulting from this practice is the low labor and machine utilization. Even for a very small planing job, all three types of machines need to be transported to site while each type of machine is used only for a rather short period of time. If only one machine of each type is employed for a small planing job, three trucks and drivers are needed only for transporting equipment. In addition to the higher equipment costs and labor costs (e.g. truck drivers' wages), there is a higher possibility that the work zone that needs to contain all needed machines is much larger than it really needs to be. This situation highlights the concerns for user costs that are caused a larger work zone and the road closures.

A potential way to avoid these problems is to combine all needed functions of each type of machine onto one or fewer number of machines. While the planing machine can provide multiple functions, the equipment operator can be trained to perform all of them, giving more flexibility to labor utilization. An analogy of this idea can be drawn from excavators that have normal excavator's function on one end and a loader's on the other. This advancement can reduce the number of trucks and drivers and the size of work zones. As a result, a lower cost planing activity can be realized and the user costs due to the work zone and road closures can be minimized.

B. Patching

Five elemental operations are identified in a patching activity [33]: (1) delineating deteriorated areas (2) removing broken or disintegrated materials (3) cleaning, drying and preparing patch areas, (4) mixing and placing patching materials and (5) compacting patching materials. From Table 4.3, it can be seen that the existing patching methods involve the intensive use of labor. Power tools such as portable rollers or hand tamps or mechanized equipment such as rollers or graders are only used to compact patching materials.

The greatest possible improvement of the current patching methods is to design a specialized machine for patching which can remove workers from the work place, where unsafe conditions are generated by working under traffic and to reduce the size of a work crew. In a patching activity, workers are normally involved in identifying a pothole, removing disintegrated materials from the pothole, cleaning and preparing the patch area and placing patching material in the pothole. With a specialized machine for patching, all the functions that are previously performed by workers can be remotely controlled by one or more operators as needed.

A manipulator arm that is controlled by the operator can be used to deliver patching material to a pothole. When preparation for the patching area, such as drying or cleaning, is necessary, compressed air can be fed via a line that is connected on the manipulator arm and be applied to the pothole. Additionally, various sensors can be placed on the specialized machine to detect conditions of the patching area and adjust characteristics of patching materials, such as temperatures or binder content, right before the filling operation takes place. A truck platform can be used to carry the patching machine so that the entire system can travel at highway speeds. Similar to rollers, the machine's weight can be used to compact the patching material, or quick curing materials which do not require compaction can be used.

The benefits that are derived from this new system are a shorter operation time, lower labor costs and the improved safety of maintenance workers, since patching activities are highly discrete in the sense that the amount of effort for any given pothole is small and moving from one location to another is required. With the current methods, crews spend a considerable amount of time in setting up the work zone, moving down tools from the truck and setting them into work. If the entire operation can be achieved by one machine, a faster operation can be easily realized. Since most functions that are practiced by human workers are replaced by the new system, the reduction of labor costs can be achieved. Also, workers' safety and working environment can be improved greatly since they no longer have to be exposed to the traffic and asphalt materials.

Various automatic patching machines have been found in the literature and are reported as successful developments. They range from simple mechanization to autonomous machines. Most of them claim a faster operation and ease of operation. The follow-up development can be numerous enhancements that will result in better quality of patching. These enhancements include the ability to detect and adjust the patching area's conditions according to the weather and ambient conditions and recycle the disintegrated materials as part of the patching material.

C. Sealing

Three elemental operations are identified in a sealing activity [33]: (1) identifying cracks or joints (2) cleaning out cracks or joints, and (3) filling sealing materials into cracks or joints. From Table 4.4, it can be observed that this activity involves the intensive use of labor. Similar to most maintenance activities, workers are required to identify and delineate the deteriorated area for operations to come. Additionally, human workers are employed to clean or rout cracks and direct sealing materials into cracks. The only large equipment, dump trucks, are used for transporting tools and materials. The tools that are used include spraying bars, router, air compressor and kettles.

TABLE 4.3 CREW SIZE AND EQUIPMENT FOR A PLANING ACTIVITY [33]

	Manual Patching	Machine Patching
Crew Size	1 Driver 2 Shovellers/Rakers 1 to 3 Flagmen	1 Grader Opr. 1 Roller Opr. 2 Shovellers/Rakers 1 to 5 Drivers (Asphalt Supply) 1 to 3 Flagmen
Equipment	1 Crew Carrier 1 Dump Truck 1 Portable Roller or Hand Tamp	1 Crew Carrier 1 Grader 1 Roller 1 to 5 Dump Trucks

The labor utilization is not very efficient in that much of the human effort is devoted to repetitive and simple operations, i.e. cleaning, routing and filling. While the operations are repetitive and simple, a more serious problem than the inefficient labor utilization is workers' safety. Safety measures around the work zone undoubtedly reduce the probability of worker injuries and fatalities. Nevertheless, the high costs of workers' compensation still makes the removal of workers from the work place highly desirable.

The opportunity of improving the current techniques stems from the introduction of an automatic system that can perform cleaning/routing and filling operations simultaneously or sequentially. Also, the mobility of the system can avoid the employment of a truck, reduce the set up time before operation and, therefore, facilitate the speed of operation. Because human workers are good at identifying and delineating patterns and severity of cracks, it may be preferable to have human workers record the crack information and then to transform workers'

knowledge of a given crack into a digital form that can later be understood and manipulated by computers that control the sealing machine.

Another direction of development is to automate the whole process. Crack detection can be fully automated with range and/or vision sensors, and the acquired information can later be used to execute the rest of the operations without operator's intervention. This direction will require more hardware investment in terms of information accuracy, computing power and system robustness than the semi-automatic approach. However, given the fact that hardware development is progressing at an explosive pace, this direction is feasible and may ultimately result in a more economic system.

One crack-filling robot which was introduced earlier in this report has drawn much attention from various research institutions and maintenance agencies. This robot can fill cracks without the intervention of human workers and may replace three workers who normally are involved in routing cracks and using the filling wands. Other potential benefits are the improved safety in terms of removing workers from the unsafe work environment and the prevention of their exposure to the volatile organics of the filling materials that can cause dermatoses and respiratory problems. More research effort is underway to reduce the image processing time and to increase the precision of filling operations.

TABLE 4.4 CREW SIZE AND EQUIPMENT FOR A SEALING ACTIVITY [33]

	Crack Sealing (Flexible Surface)	Joint Sealing (Rigid Surface)
Crew Size	2 Drivers 1 Sweeper 2 Router/Comp. Air Oprs. 1 Spray Bar Opr. or 2 Pourers 1 to 2 Drivers or 1 to 3 Flagmen (Traffic Control)	1 Foreman 2 Drivers 1 Router Opr. 2 Sealant Installers 1 to 2 Drivers (Traffic Control)
Equipment	1 Crew Carrier 1 Dump Truck 1 Kettle Air Compressor Router 1 or 2 Sign Trucks/Sign Trailers	1 Crew Carrier 1 Dump Truck 1 Compressor 1 Joint Router 1 Kettle 1 or 2 Sign Trucks or Sign Trailers

D. Surface Dressing

Four elemental operations are identified in a surface dressing activity [33]: (1) identifying and locating deteriorated areas, (2) placing surface dressing materials, (3) spreading aggregate on surface, and (4) compacting and finishing dressing area. Since surface dressing is a treatment for restoring road skid resistance or road evenness within a small area, it involves very little use of machines. Even though equipment is available, human workers are used to place dressing materials and spread aggregates. The compacting force for the dressing area is primarily provided by the weight of a truck or a loader.

Since surface dressing is used infrequently and can only serve for a short-term purpose, it does not attract much attention for technological advancements. As a result, it is not very likely that a specialized machine for surface dressing will receive a very high priority for development. Nevertheless, an opportunity stems from applying other specialized machines to achieve this activity. For instance, a patching machine that is normally adaptive to handle aggregate materials can be equipped with the additional function to deliver fluid and viscous material, such as binding materials.

The idea of using one specialized machine for other purposes brings up the issue of designing a multifunctional machine for road maintenance. This concept has been around for some time. The use of human workers and general-purpose machines is one common example. A work crew that is designated to repair a pothole in a given location may find itself able to apply additional remediation, such as surface dressing treatment in the adjacent area, simply because the functionality of a human work crew and general-purpose machines are numerous and highly flexible.

E. Thin Overlays

Four elemental operations are identified in a thin overlay activity [33]: (1) identifying and locating the deteriorated areas (2) preparing and placing screeds or other material-controlling device (3) mixing and placing surfacing materials, and (4) compacting and finishing surface materials. By examining Table 4.6, it is found that the last two (3 and 4) operations are done through the use of general-purpose machines, such as rollers, power brooms, aggregate spreaders, loaders, etc. Human workers are primarily used for the first two (No. 1 and No. 2) operations.

TABLE 4.5 CREW SIZE AND EQUIPMENT FOR A SURFACE DRESSING ACTIVITY [33]

Surface Dressing	
Crew Size	2 to 3 Drivers 1 Spray Bar Opr. 2 Shovellers 1 Loader Opr. 1 to 3 Flagmen
Equipment	1 Crew Carrier 1 to 2 Dump Trucks 1 Kettle 1 Loader

The greatest opportunity for technological advancement for this activity can be illustrated by examining the types of equipment that are involved. A total of five types are used for a maintenance unit: distributors, aggregate spreaders, loaders, rollers, and power brooms, not to mention the transportation equipment. While a faster speed of operation can be realized by employing them, a vast portion of the work zone is used to contain the equipment while not in use. Often the required size of the work zone is so large that a complete road closure is inevitable. As mentioned earlier, as the number of machines increases, the labor as well as machine utilization tends to be lower, resulting in a higher cost.

Advancements can be made towards the design of a mechanized device with sensors that can substitute for the two tail-end operators on the aggregate spreader and control the spread of aggregate and binding materials evenly throughout the entire road section. This mechanized device can be equipped with a roller platform, so that the entire operation can be done by one machine with one pass.

TABLE 4.6 CREW SIZE AND EQUIPMENT FOR A THIN OVERLAY ACTIVITY [33]

Thin Overlays		
Crew Size	1 Foreman 2 Distributor Oprs. 2 Tail-End Oprs. 2 Aggregate Spreader Oprs. 1 Loader Opr.	1 Wobble Wheel Roller Opr. 1 Steel Wheel Roller Opr. 1 Driver (Broom and Convoy) 1 Broom Helper/Flagman 2 Flagmen (Traffic Control)
Equipment	1 Convoy and Crew Carrier 2 Distributors 1 Aggregate Spreader 1 Loader 1 Wobble Wheel Roller	1 Steel Wheel Roller 1 Trailer Type Power Broom 1 Dump Truck 1 Trailer

Another advancement opportunity is to combine the functions of a power broom onto the roller platform. This enhancement is possible because the types of motions of both systems are progress-by-rolling. One possible system configuration is to have a lighter wheel that performs the function of brooming and the other wheel which is much heavier provides the necessary force for compacting. The heavier wheel will compact the overlay first, then the lighter wheel can clean the road surface.

While safety is not a major driving factor for this technological advancement, because traffic is usually diverted to other routes, the perceived benefits in this activity are the lower costs of operation and a shorter duration of road obstruction by maintenance activities. The lower costs are realized by replacing human workers (tail-end operators) with mechanized methods, and the faster operation is resulted from fewer number of machine changeover and setup.

CHAPTER 5 ECONOMIC ANALYSIS OF TECHNOLOGICAL ADVANCEMENTS

This chapter will investigate the economical feasibility of technological advancements for road maintenance. Crack sealing, whose opportunity has been assessed in Chapter 4, will be examined closely in terms of its maintenance costs. An automated crack sealing system will be included in the economic analysis of technological advancements. The analysis in this Chapter is based on a study conducted in the Carnegie-Mellon University [34].

5.1 PRACTICE OF CRACK SEALING IN THE US

Crack sealing is a common maintenance activity that is practiced by various maintenance agencies. According to *Highway Statistics* [1], there are four groups of agencies that are responsible for road maintenance: states, municipalities, counties & townships and toll facilities. Based on the results of the questionnaire survey in [34], the maintenance expenditures of these four groups in the year of 1989 is presented in Table 5.1. It is found that roughly \$190 million represent national expenditures on crack sealing, but excluding expenditures by private organizations, the military and airports.

TABLE 5.1 MAINTENANCE EXPENDITURES BY AGENCY IN 1989 [34]

Agency	Mean of Expected Expenditure %	Total O&M (in million \$)	Amt for Crack Filling (in million \$)
States	0.69	7761	53.3
Municipalities	1.5	5707	85.9
Counties & Townships	0.83	5529	46.1
Toll Facilities	0.18	1212	2.2
Total			187.5

As identified in the previous chapter and [27, 28, 29, 34], crack sealing relies heavily on the use of labor. For the states using agency forces, crack filling appears to be an activity undertaken by multi-functional maintenance crews on an as-required basis. Also, on average, crews are involved in crack sealing 25% of the time for 6 months in a year, with a crew size ranging from 14 to 3 or an average of 7. Labor costs vary from \$5.11/hr to \$23.04/hr with an average of \$12 for a laborer, not necessarily including overhead and profit.

5.2 ECONOMIC ANALYSIS OF AUTOMATED CRACK SEALING

To develop an estimate of the number of crack sealing units likely to be used by states if they were available, the analysis will focus on crack sealing by agency forces. In the questionnaire of the previous study, 35 states indicated that they would use an automated crack sealing system which represents potentially 1800 crews. With the assumption that crews are involved in crack sealing 25% of the time for six months of a year and an automated system could be shared between four crews, it is expected that 450 units (1800 crews/ 4 crews per unit) are required nationally.

Assuming that three of the seven workers, who would normally be involved in cleaning the crack and using the filling wands, can be replaced by an automated system, the expected labor savings are estimated to be:

$$\frac{3 \text{ Laborers}}{\text{Crew}} \times \$12/\text{hr} \times 25\% \times 2000 \text{ hrs/yr} \times \frac{6 \text{ Months}}{12 \text{ Months}} = \$9,000 \text{ per year per crew}$$

Life cycle costs for the system include acquisition costs, and annual operating and maintenance costs [35]. The system acquisition costs are estimated to be \$100,000 per unit based on the breakdown of costs given in Table 5.2. Annual maintenance and operating costs of \$10,000 per unit are based on the following assumptions:

- Software maintenance: \$2,500/year
- Energy expenditures: \$2,500/year
- Set-up and dismantling costs: \$500/year
- Transportation costs between job sites: \$1,000/year
- Maintenance and repair: \$3,500/year

The system life is assumed to be 6 years based on 6 months operation per year and regular maintenance.

Using these cost estimates for the automated system and estimates for the labor savings, the difference in expenditures using the automated rather than the manual method can be developed. Using a discount rate of 5%, a system life of 6 years (with the equipment only being utilized for 6 months in any one year), and productivity comparable to existing procedures, the net present value of the additional cost (acquisition, maintenance and operating) of the automated system is \$150,760. When

TABLE 5.2 CAPITAL COST BREAKDOWN [34]

Item	Costs (in thousand dollars)
Computing	10
Generator and UPS	8
Controllers and Motors	5
Camera and Boom	10
x-y table and Trailer	10
Other	17
Engineering, Assembly and Manufacturing	40
Total Capital Cost	100

subtracted from the labor savings over the life of the system of \$182,736, the net labor savings are \$31,976 per unit over the life of the system or \$6,300 per unit per year. As mentioned, annual crack filling expenditures by states were estimated to be \$53.3 million per year and it is expected that 450 units will operate nationally. This gives a national saving of approximately \$14.4 million over the 6 years life of the equipment or \$2.84 million per year or 5.3% of estimated expenditures by states for crack sealing.

The analysis shows that automated crack sealing is economically feasible and desirable. As this analysis is based on survey responses, the following limitations should be noted:

1. The survey responses may not represent a random sample due to biases introduced by non-responses.
2. Actual labor costs may be higher, as reported labor costs are significantly less than figures including overhead in Means Cost Data [35]. Therefore, larger savings may be realized.
3. Analysis focuses on crack sealing by state public works or department of transportation crews that work on crack sealing as just one of many maintenance operations. Additional crack sealing units and ultimately labor savings will be realized as contractors adopt automated crack sealing. Additional savings may also be realized if organizational changes occur and specialized crack sealing crews are used to ensure more effective utilization of the equipment.

5.3 BENEFITS OF AUTOMATED CRACK SEALING

From the economic analysis, it is concluded that the automated crack sealing system can pay for itself. Nevertheless, it is important to note that the benefits of automated crack sealing are not just the savings in direct costs of maintenance operations. This new technology is safer because workers

do not expose themselves directly to the traffic. It also has very high potential in improving the quality of crack sealing as cracks are accurately identified, uniformly cleaned and potentially, material delivered at a rate appropriate to the depth and width of the crack.

The higher quality of crack sealing will increase the durability of road pavement. The longer pavement life will minimize the frequency of resealing and the "action" user costs due to delays for resealing pavement cracks or undertaking other maintenance activities. Also, the capacity of maintenance forces can be easily expanded simply by purchasing more such systems. Consequently, maintenance forces can be more responsive to road cracks and reduce the time lapse between crack formation and sealing. By so doing, the "non-action" user costs, especially the vehicular operating costs, can be reduced significantly.

CHAPTER 6 SUMMARY ANALYSIS

From this study, it is found that tremendous needs for technological advancements exist in road maintenance. These needs include reducing the labor requirement of current maintenance practices as well as removing workers from potential danger and hazard, shortening the lane closure time by faster maintenance operations, minimizing the size of a work zone and the interference between maintenance crews and the traffic, increasing the capacity of maintenance forces to reduce the time lapse between defect formation and repair, extending the flexibility of maintenance forces in terms of working at night and under bad weather conditions, improving the quality of current maintenance techniques, and conforming environmental regulations.

If these needs can be met by technological advancements, two major categories of costs directly or indirectly related to road maintenance can be reduced: (1) the direct costs of maintenance operations, and (2) the user costs. The possible cost reduction in the first category includes the labor costs, the accident costs of maintenance workers, and the overhead. All of these three possible reductions stem from a better practice of labor employment.

The user costs can be reduced by minimizing the number of accidents that are related to road maintenance activities, minimizing the travel time that is wasted in slowing down speeds and waiting in queue to pass a work zone, avoiding complete road closures which often require traffic diverting to other routes, and reducing the fuel consumption and vehicular operating and maintenance costs of highway driving.

In addition to the possible cost reductions in these two categories, other intangible benefits of technological advancements in road maintenance can be realized. For road users, the ease of driving can be experienced with better road serviceability. For maintenance crews, technology can provide for a better work environment and enrich job content.

This study has focused specifically on automation technology as one major area of technological advancements in road maintenance. Fifteen automated systems in road maintenance are identified that are being used for defect surveys, traffic control, and defect treatment. These systems prove that automation technology is technically feasible and it can meet the needs for technological advancements in road maintenance.

This study also illustrates that automated maintenance can be economically feasible. An economic analysis of crack sealing shows it can save a total of \$2.84 million per year nation wide. It is important to point out that the monetary savings in this example are derived solely from the reduction of direct costs of maintenance operations. The possible user benefits are not assessed. In other words, this technology will pay for itself and it is economically feasible for maintenance forces to invest in this system, without any consideration of the possible reduction in user costs.

However, the corresponding possible reduction in user costs should not be overlooked or underestimated whenever maintenance forces are considering adopting new technologies for road maintenance. Most importantly, technological advancements should not be discouraged only because it is not economically feasible for maintenance forces to invest in certain technology. In the case of automated crack-sealing system, for example, if the user benefits that can be generated each year by shortening the lane closure time approach \$5 million and the maintenance forces *spent* \$2.84 million more (instead of saving) per year with this new technology, it is still necessary for maintenance forces to consider investing and implementing this system simply because road users will save money and public economy will benefit.

In this study, the user benefits have been assessed in two major areas. In the possible reduction of the "action" costs, significant savings can be obtained by shortening the lane closure time and minimizing the size of a work zone. As illustrated in the examples, road users spend at least \$9.2 million (for 200 lane closures) annually in Texas on waiting, extra fuel consumption, and extra vehicle operating and maintenance expenses for passing work zones that contain crack sealing activities. If, with the introduction of the automated crack-sealing system, the operation time can be reduced by 10%, the immediate user benefits are close to \$1 million savings in Texas or tens of million dollars nationwide.

For "non-action" user costs, significant user benefits can be realized by shortening the time lapse between defect formation and repair. In the preliminary analysis of this study which assumes the International Roughness Index of a road will descend from 2.2 (good condition) to 8.8 (poor condition) after twenty years of service, it is calculated that road users spend \$83,921 annually in vehicular operating costs for each mile of driving on such roads. If we further assume that out of all paved roads in Texas which totaled slightly more than 300,000 miles in 1990), there

are 300 miles of roads in such conditions, the user costs in this category are \$25.2 million each year. This incurs a even greater expenses than that of the "action" user costs.

Clearly, increasing the capacity of maintenance forces is a prerequisite to shorten the time lapse between defect formation and repair, provided that timely defect information can be reported by road surveys. With automated systems, there are fewer limitations on expanding the capacity of maintenance forces. The abilities of an automated system can be easily duplicated. With less human involvement, such systems can perform maintenance operations day and night and in most weather conditions. If, with automated systems, maintenance forces are able to expand their capacity and reduce the time lapse between defect formation and repair by 10%, user savings are in the range of two to three million dollars each year in Texas or possibly more than \$100 million in the nation.

CHAPTER 7 CONCLUSIONS

In summary, the major conclusions of this study are as follows:

1. Automation in road maintenance is technically feasible and will pay for itself.
2. Minimizing the labor employment in road maintenance is a key issue in reducing the direct costs of maintenance operations.
3. The emphasis of R&D for automation in road maintenance should be placed on minimizing "action" and "non-action" user costs, instead of reducing the direct costs of maintenance operations.
4. To minimize the "action" user costs, the R&D effort should be placed on shortening the required operation time and the size of work zones.
5. To minimize the "non-action" user costs, the R&D effort should be placed on shortening the time lapse between defect formation and repair. This implies that timely information of defect surveys should be provided and that the capacity of maintenance forces needs to be expanded by the employment of automated systems.
6. As predicted earlier in this study, the demand for road maintenance will increase rapidly over the upcoming years. Maintenance forces around this country should act promptly in answering the demand.

REFERENCES

- [1] *Highway Statistics*, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1980.
- Highway Statistics*, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1981.
- Highway Statistics*, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1982.
- Highway Statistics*, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1983.
- Highway Statistics*, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1984.
- Highway Statistics*, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1986.
- Highway Statistics*, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1988.
- Highway Statistics*, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1989.
- Highway Statistics*, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1990.
- Highway Statistics*, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1991.
- [2] *AASHTO Maintenance Manual*, American Association of State Highway and Transportation Officials, Washington, D.C., 1987.
- [3] Memmott, J. and Dudek, C. (1984). "Queue and User Cost Evaluation of Work Zone (QUEWZ)," *Transportation Research Record* 979, pp. 12-19.
- [4] Memmott, J. and Dudek, C. (1982). "A Model to Calculate the Road User Costs at Work Zones," Technical Report FHWA/TX-83/20+292-1, September.
- [5] *HDM-PC, The Highway Design and Maintenance Standard Series*, World Bank, Washington, D.C., January, 1989.
- [6] Skibniewski, M. and Hendrickson, C. (1990). "Automation and Robotics for Road Construction and Maintenance," *Journal of Transportation Engineering*, ASCE, Vol. 116, No. 3, pp. 261-271.
- [7] Skibniewski, M. and Hendrickson, C. (1988). "Analysis of Robotic Surface Finishing Work on Construction Site," *Journal of Construction Engineering and Management*, ASCE, 114(1), pp. 53-68.

- [8] Goetsch, D.L. (1988). *Fundamentals of CIM Technology*, Delmare Publishers, Inc., Albany, N.Y.
- [9] Haas, C., Hajek, J. and Haas, R. (1991). "Opportunities for Automation in Pavement Maintenance," *Proceedings of the Annual Conference of Transportation Association of Canada*, Winnipeg, September.
- [10] Fukuhara, T., Terada, K. and Nagao, M. (1990). "Automatic Pavement-Distress-Survey System," *Journal of Transportation Engineering*, ASCE, Vol. 116, No. 3, pp. 280-286.
- [11] Hudson, R., Elkins, G., Uddin, W., and Reilley, K.(1987). "Improved Methods and Equipment to Conduct Pavement Distress Surveys," *Technical Report FHWA-TS-87-213*, April.
- [12] PASCO USA Inc. (1985). "Report on Pavement Condition Monitoring Methods and Equipment," Lincoln Park, N.J., September.
- [13] MAP Inc. (1986) "Pavement Condition Monitoring Methods and Equipment Final Report on GERPHO," Washington, D.C., August.
- [14] Dewilder, M. (1985). "GERPHO and the APL," *Roadway Evaluation Equipment Workshop, Proceedings, Report No. FHWA-TS-85-210*, May.
- [15] "1 for 3, PASCO Road Survey System (PRS-System) - From Theory to Implementation," PASCO Corporation, c/o MITSUBISHI International Corporation, Project and Development Div., New York.
- [16] Highway Products International, Inc., "Automatic Road Analyzer - Mobile Data Acquisition Vehicle," *Product Bulletin*, 1985.
- [17] Novak, R. (1985). "Swedish Laser Road Surface Tester," *Roadway Evaluation Equipment Workshop, Technical Report FHWA-TS-85-210*, May.
- [18] Infrastructure Management Service (1986). "Interim Memorandum to Waheed Uddin," September.
- [19] Addco Manufacturing Co., Literature, St. Paul Minnesota, 1990.
- [20] Connecticut Tries Movable Barrier, *Better Roads*, June, 1990.
- [21] Horizon Signal, Literature, Wayne, Pa., 1990.
- [22] Smith, K. (1991). "Work Zone Safety Devices Slated for State Trials This Year," *Strategic Highway Research Program Focus*, April.
- [23] Thorpe, C. (1989). "Outdoor Visual Navigation for Autonomous Robots," *Proceedings of Intelligent Autonomous Systems II Conference*, Amsterdam, December.
- [24] Rollings, R., Korgemagi, P., and Lynch, D. (1985). "An Evaluation of a High Production Integral Spray Patcher," *Public Works*, January, pp. 55-58.

- [25] RQS Industries, Inc. (1990). Literature, Joplin, Mo.
- [26] University of Alaska Fairbanks (1991). Alaskan Transportation Technology Transfer Program - Planning, Design and Field Notes.
- [27] Haas, C., Hendrickson, C. and McNeil, S. (1991). "A Design for Automated Pavement Crack Sealing," Proceedings of the ASCE Construction Congress, Cambridge, MA.
- [28] Haas, C. (1990). "A Model of Pavement Surfaces," unpublished PhD dissertation, Department of Civil Engineering, Carnegie-Mellon University.
- [29] Haas, C., Hendrickson, C., McNeil, S. and Bullock, D. (1992). "A Field Prototype of a Robotic Pavement Crack Sealing System," Proceedings of the 9th International Symposium on Automation and Robotics in Construction, Tokyo, Japan, pp 313-322, June.
- [30] Coomasary, C. (1991). "Pavement Markings Equipment," Ministry of Transportation of Ontario, Ontario, Canada, June.
- [31] Point, G. (1988). "Two Major Innovations in Current Maintenance: The Multipurpose Vehicle and the Integrated Surface Patcher," presented at the Transportation Research Board Annual Meeting, Washington, D.C.
- [32] *Techniques for Road Surfacing Maintenance*, Organization for Economic Co-operation and Development, Paris, France, October, 1978.
- [33] *Pavement Maintenance Guidelines*, Ministry of Transportation and Communications, Ontario, Canada, September, 1980.
- [34] Deng, J., Pearce, A., and McNeil, S. (1992). "Economic Analysis of Automated Pavement Crack Sealing," Technical Report SHRP IDEA-87-ID017, March.
- [35] *Means Facilities Cost Data*, R.S. Means Company, Inc., Kingston, MA, 1990.

Appendix

Exhibitions of Some Automated Systems in Road Maintenance

1. Automatic Pavement-Distress-Survey System

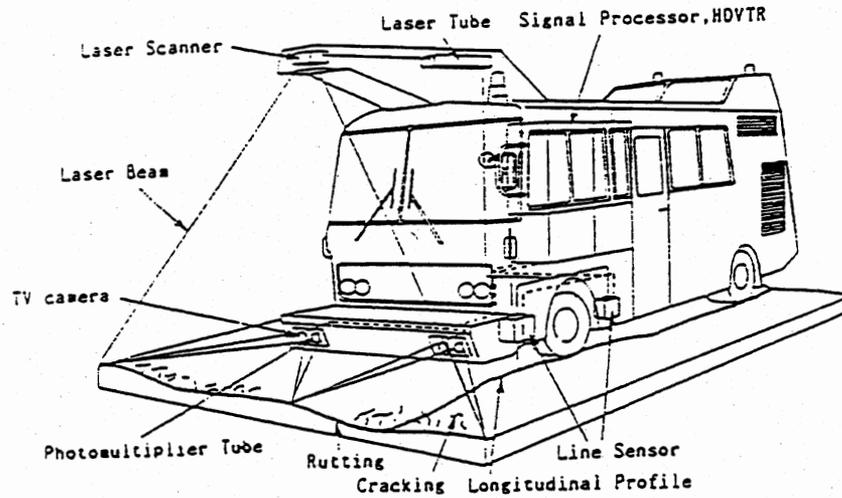


Figure A.1 Pavement-Distress-Survey Vehicle [10]

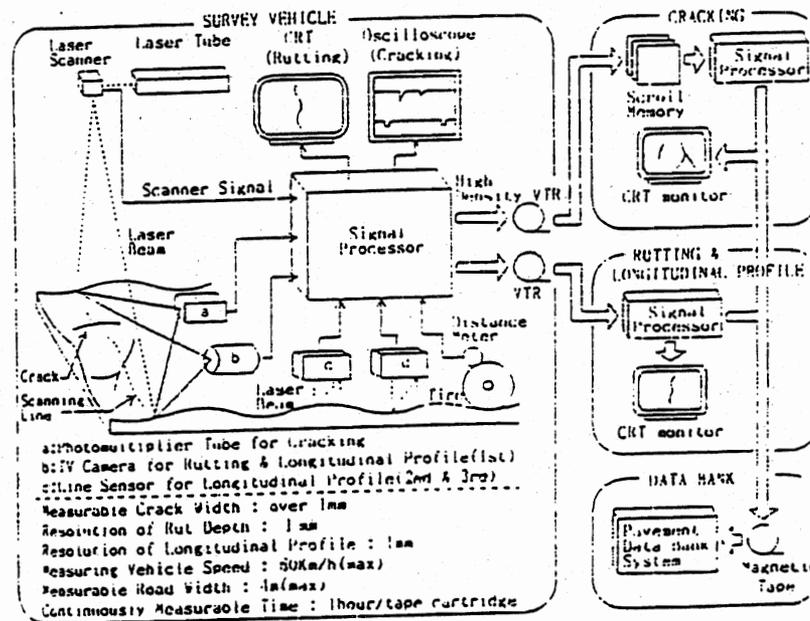


Figure A.2 Flow Diagram of Pavement-Survey System [10]

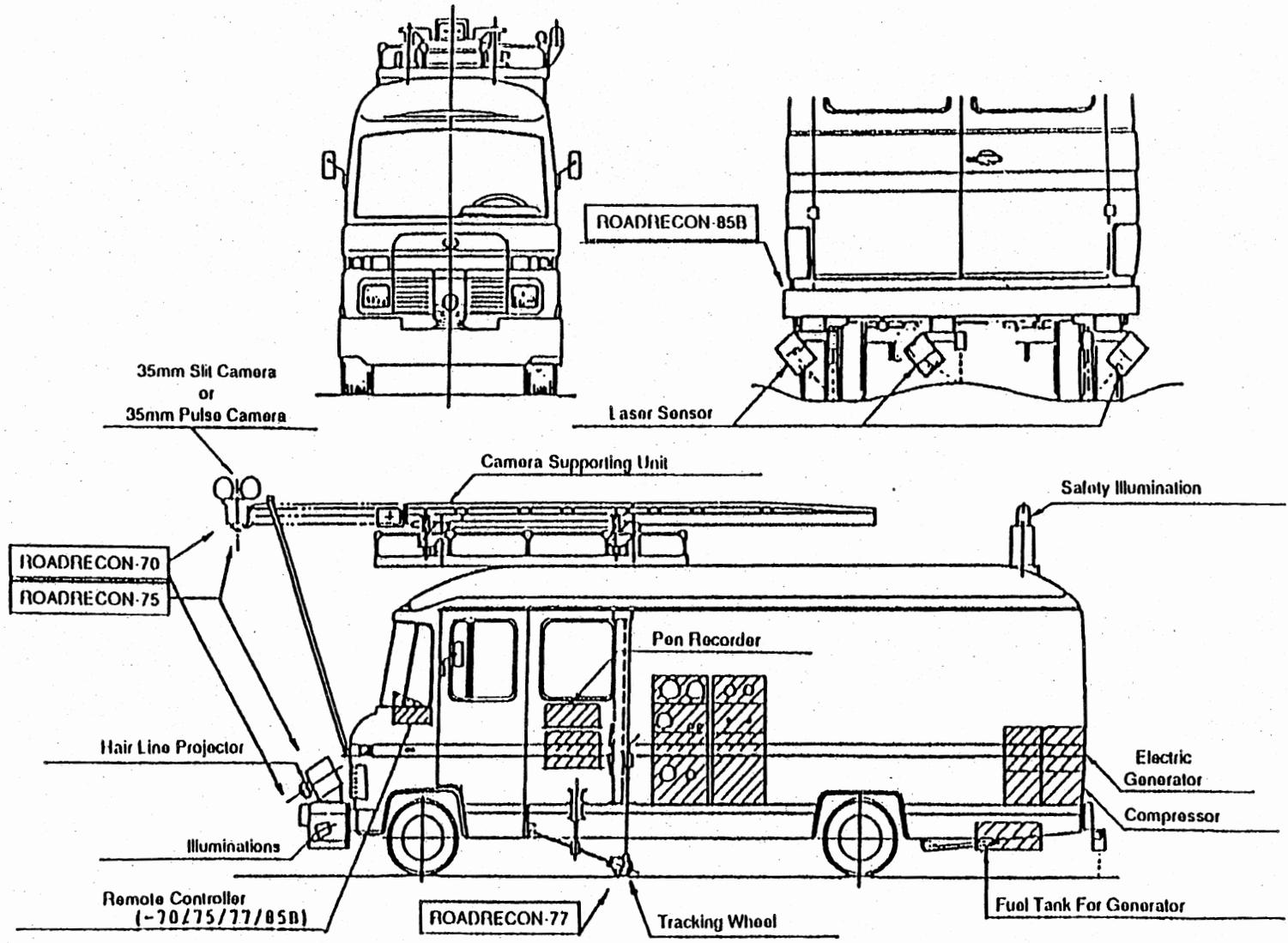


Figure A.3 A Schematic Illustration of PASCO ROADRECON System [11]

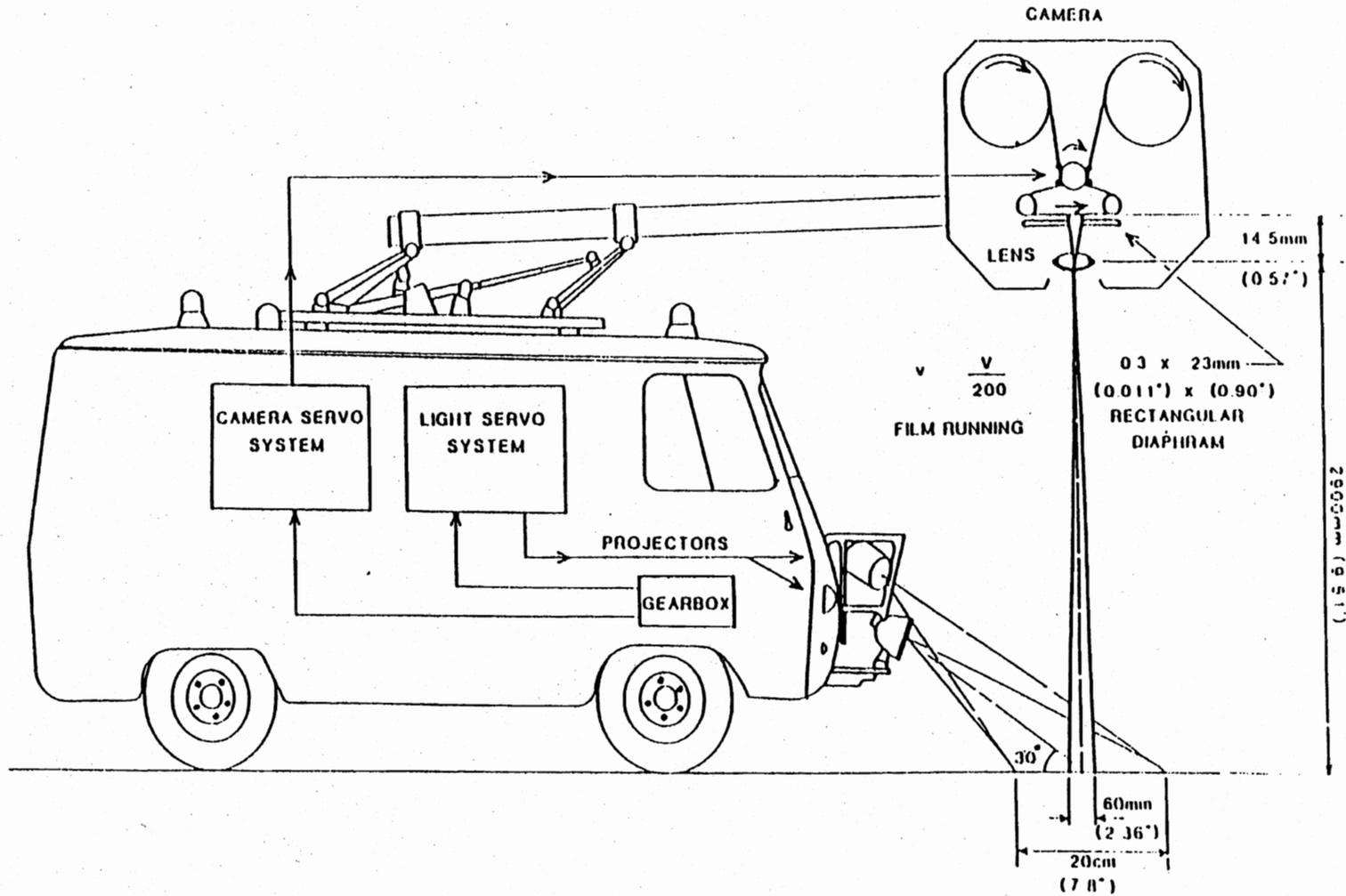


Figure A.4 A Schematic Illustration of GERPHO [11]

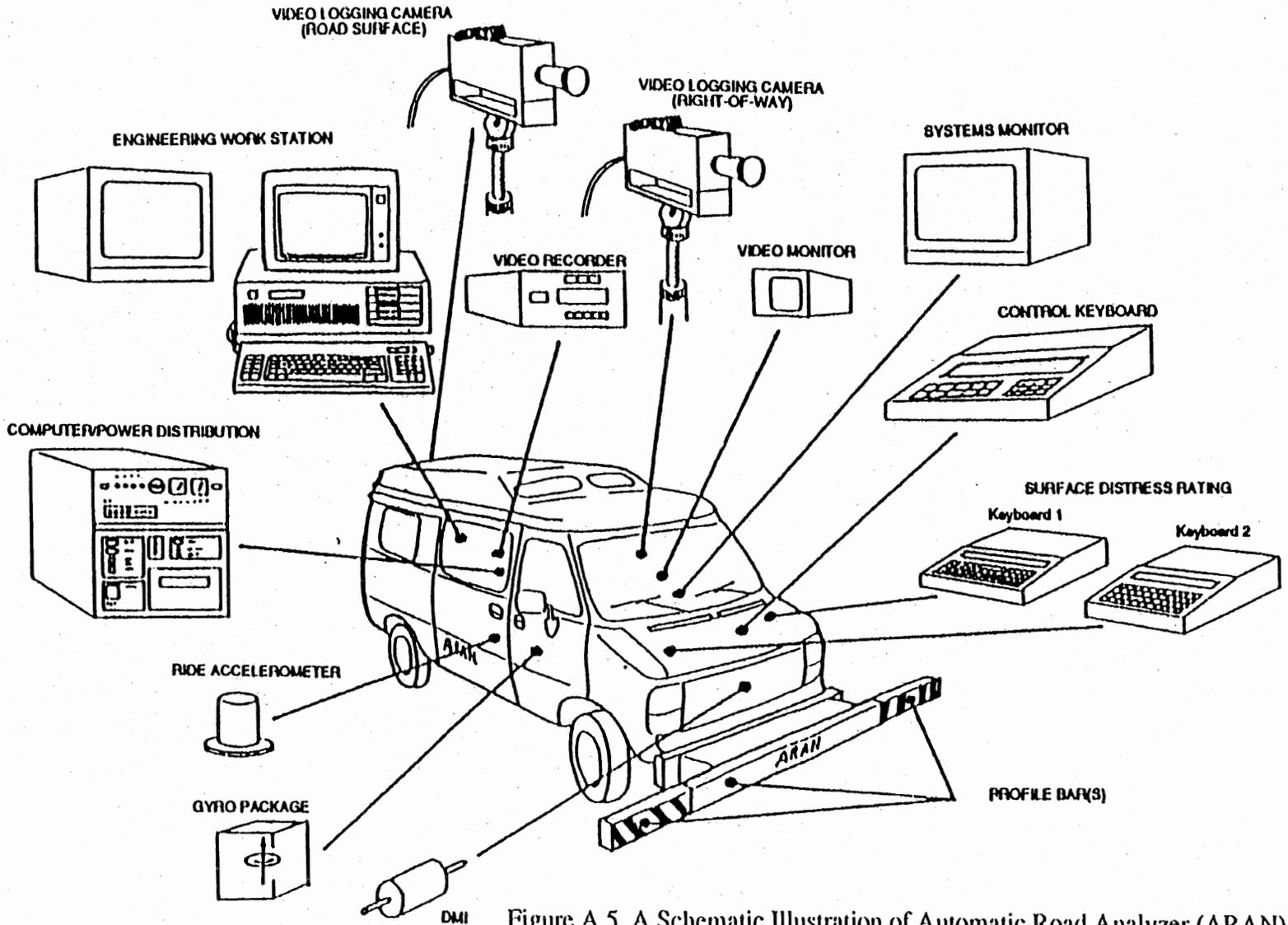


Figure A.5 A Schematic Illustration of Automatic Road Analyzer (ARAN) [11]

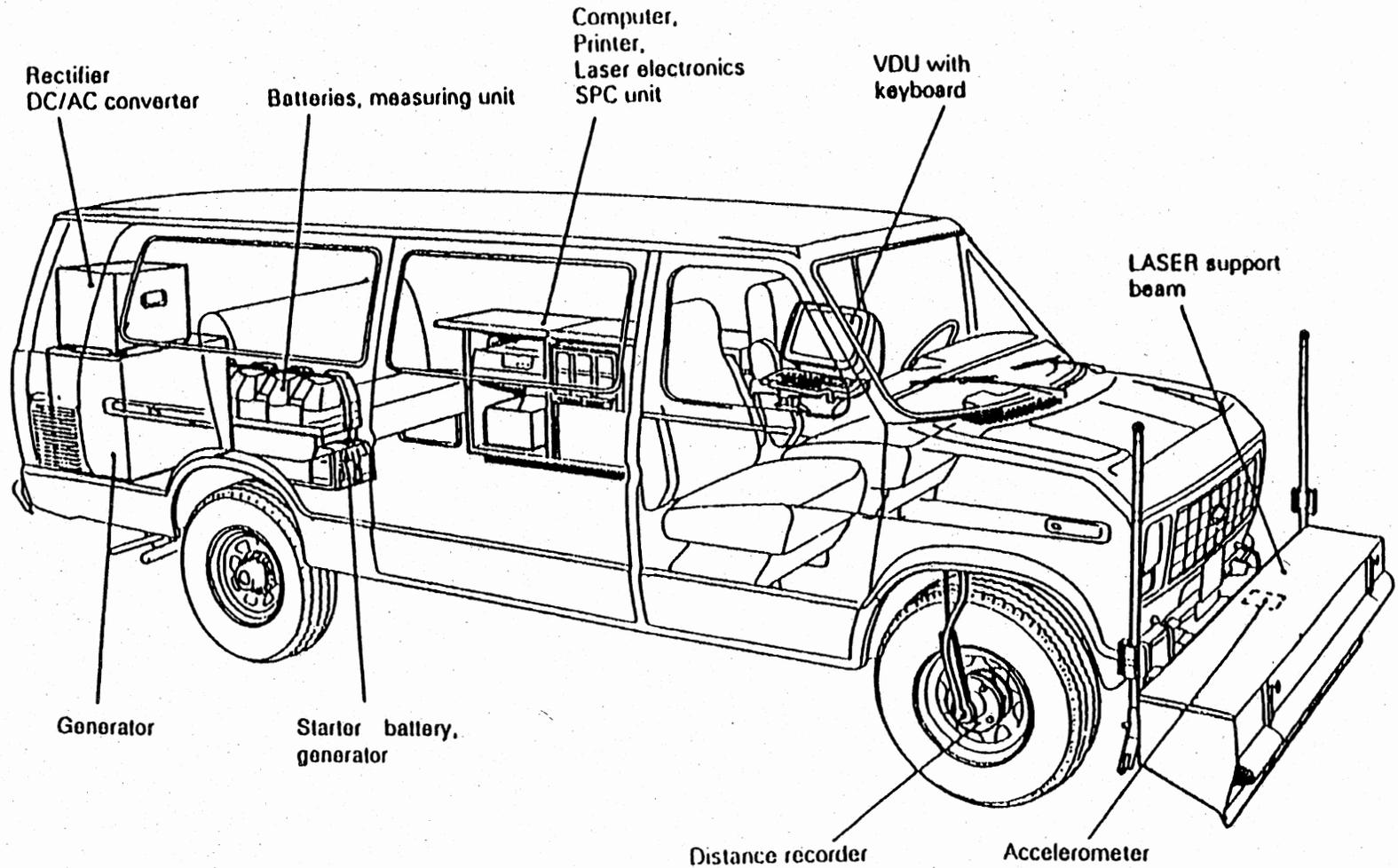


Figure A.6 A Schematic Illustration of Laser Road Surface Tester (RST) [11]



Figure A.7 A Schematic Illustration of Quickchange Movable Barrier System [36]

7. Automatic Crack-Filling Robot

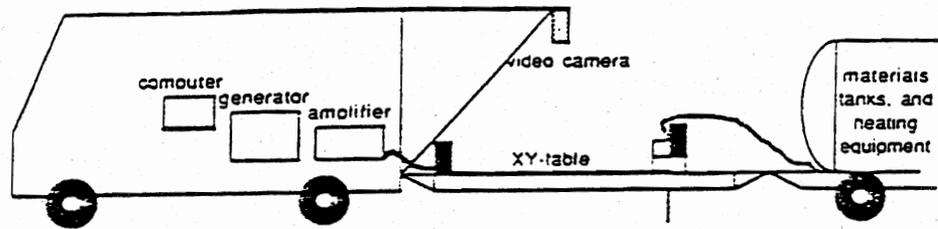


Figure A.8 A Schematic Illustration of the Crack Filling Robot System [29]

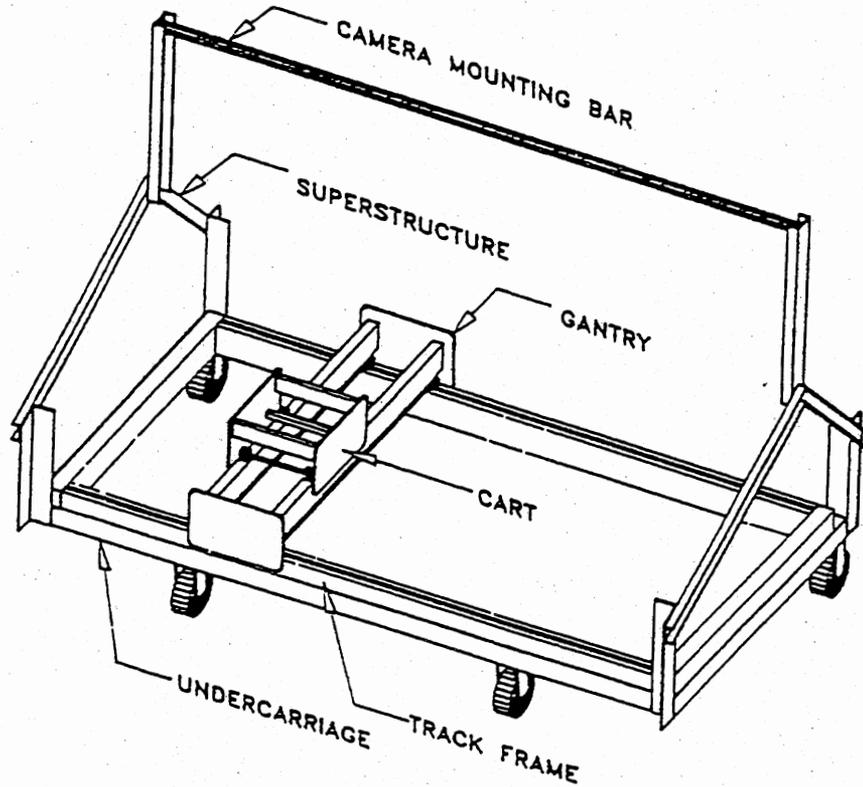


Figure A.9 X-Y Table Conceptual Design [29]