# Costs and Benefits of Automated Road Maintenance

TING-YA HSIEH AND CARL T. HAAS

Because of increasing maintenance demands and the increasing impact of maintenance operations on users, there is a tremendous need to improve maintenance technology. By improving maintenance technology, the direct costs of maintenance operations and the related user costs can be reduced. Automation technology for reducing such costs is examined. Specifically, 22 automated systems in road maintenance are identified that are used for defect surveys, traffic control, defect treatment, and other supportive activities. These systems demonstrate that automation technology is technically feasible and that it could meet the needs for technological advancements in road maintenance. The study also illustrated that automated maintenance can be economically feasible. For example, one economic analysis of crack sealing shows that it could save at least $3 million/year nationwide in operations costs. However, the corresponding potential to reduce user costs by minimizing the interference of maintenance operations with traffic is even greater. Future development of maintenance technologies should therefore focus primarily on reducing user costs as well as operations costs.

As the North American road system ages, traffic volume increases, environmental regulations proliferate, and the direct costs of maintenance grow, maintenance agencies are faced with the resulting increasing demands on maintenance activities. At the same time, road maintenance technology has remained virtually unchanged in many respects for decades. Small-scale, dispersed activities are performed under traffic conditions by generally low skilled laborers with basic equipment. Such conventional road maintenance methods may be inadequate to meet the increasing demands.

Automation technologies present opportunities to improve maintenance methods and to meet the objectives of maintenance agencies. In addition to maintaining a safe and comfortable driving environment, these objectives include reducing operating and user costs. Decreasing the operating costs of maintenance through automation will allow agencies to increase their forces and lower user costs resulting from delayed maintenance. Automated systems that can operate more quickly and in a wider range of environmental conditions will reduce lane closure time and traffic interference, again reducing the related user costs.

The benefits of automated maintenance in terms of lower user and operational costs result from the potential of automated maintenance to minimize interference with traffic, increase the flexibility and capacity of maintenance forces, improve work quality, reduce labor requirements, improve worker utilization, conform to environmental regulations, and remove workers from danger. Automated maintenance costs include development, capital acquisition, and operating costs. The economy of automated maintenance depends on the perspective taken, but in most cases the benefits outweigh the costs.

This paper examines the costs and benefits of developing and implementing automated road maintenance. After discussing the characteristics of road maintenance, the user costs of road maintenance, and the costs and benefits of automating road maintenance, the resulting economics are discussed. A recent survey of existing automation applications in road maintenance is also presented. In an attempt to illustrate broadly the magnitude and balance of the costs and the benefits of automated road maintenance, this paper is only the first stage of a more extensive and detailed quantitative research program. [For a broad introduction to road construction and maintenance automation, the reader should refer to work by Skibniewski and Hendrickson (*1*).]

## CHARACTERISTICS OF ROAD MAINTENANCE ACTIVITIES

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 while driving. Thus, the objectives of road maintenance activities are to restore road skid resistance and road evenness and to maintain road impermeability.

Current conventional road maintenance activities are characterized by the following:

- Small-scale operations,
- Dispersed locations,
- Work under traffic,
- Labor-intensiveness,
- Relatively low skill level of laborers,
- Off-peak work hours, and
- Affected by weather conditions.

These characteristics distinguish road maintenance from road construction and most other construction activities. They affect the design of maintenance equipment and techniques, the organization of maintenance crews, and the management of maintenance activities as well as resources. These characteristics indicate that conventional road maintenance methods may not be flexible enough to meet the changing maintenance demands and trends identified previously. As a result, road

T. Hsieh, Department of Civil Engineering, ECJ 5.412, University of Texas, Austin, Tex. 78712; current affiliation: Department of Civil Engineering, National Central University, Chung-Li, Taiwan, 32054 Republic of China. C. T. Haas, Department of Civil Engineering, ECJ 5.200, University of Texas, Austin, Tex. 78712.

users—drivers and passengers alike—inevitably, and sometimes unknowingly, spend enormous amounts of additional time and money in highway travel. These expenditures are normally described as user costs.

## USER COSTS RELATED TO ROAD MAINTENANCE

User costs related to road maintenance include travel delays, vehicular operating costs (including fuel consumption), vehicular maintenance costs, and accident costs. User costs are incurred when roads need maintenance and repair and when roads are actually undergoing maintenance and repair work.

A breakdown of the user costs concerning these two categories is shown in Figure 1. As can be seen from the figure, the user costs incurred when roads are undergoing maintenance and repair work are relatively easy to measure. The computerized cost model QUEWZ (Queue and User Cost Evaluation of Work Zone) (*2,3*) can be used to estimate the repair "action" user costs. The repair "nonaction" user costs, or costs incurred when roads are in need of repair, are more complex to measure as the time lapse between a defect formation and its 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 difference from one vehicle to another. The computerized cost model HDM-III (Highway Design and Maintenance Standards Model) (*4*) can be used to estimate the nonaction user costs. This paper uses these models to estimate the order of magnitude of the benefits that may be accrued by improving road maintenance technology.

### Nonaction Costs

#### *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. Additional vehicular operating costs attributed to 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 traveling across the road defect. Defects may be aggregated for calculations.

#### *Costs of Accidents to Road Users*

Accident costs due to delayed maintenance are real but are difficult to estimate. The cost model used here excludes the calculation of accident costs.

#### *Deterioration of Existing Roads*

After a road defect is formed, every vehicle crossing it will cause damage to the defect. The cumulative cost of this effect is incorporated in HDM-III.

#### *Decreased Usage of Defective Roads*

As the deterioration process of the defects continues, some road users may choose other routes to substitute for the de-

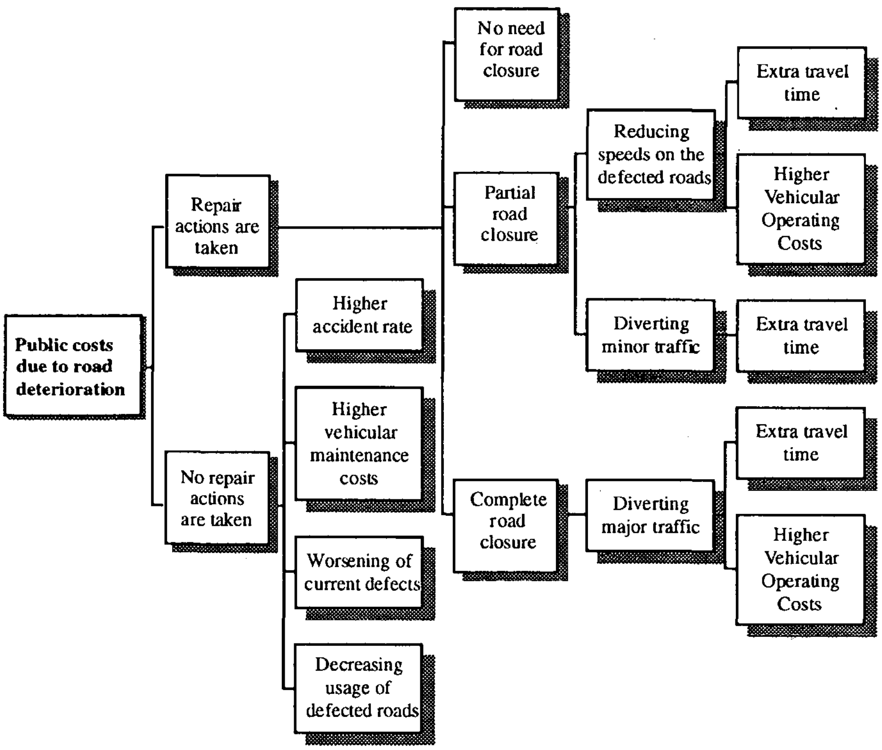


**FIGURE 1 Cost breakdown structure of user costs.**

teriorated one, thus imposing delay costs on themselves and adjacent route traffic.

### Action Costs

#### *Costs of Extra Travel Time*

The extra travel time is due to the lower average travel speeds and the longer travel distance. When a work zone completely blocks the defective road section, highways must be provided to connect the road to other temporary or existing roads before and after that section. If highways 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 the potential traffic congestion. 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. The travel time for that particular section is increased due to the slower traffic resulting from the lower speed and the potential traffic congestion.

#### *Additional Vehicular Operating Costs*

The additional vehicular operating costs can be divided into two categories: costs due to extra travel and those due to waiting, stop-and-go cycles, and lower average speeds. The first category 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 costs of slowing down and returning to the approaching speed as a result of the presence of a work zone and the speed-change cycles in queueing. The second aspect deals with the higher operating costs when the average travel speed is lower. Simply put, when a vehicle travels at a very low speed, the fuel consumption and the vehicular maintenance needs tend to increase.

### Calculation of User Costs

#### *Calculation of Nonaction User Costs*

HDM-III, 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 HDM-PC Version 2.0 (*4*) calculations show that delayed maintenance can increase vehicle operating costs in the United States by tens of millions of dollars a year. Improving maintenance agencies' force capabilities by improving maintenance technology should help reduce user costs due to inaction by millions of dollars a year.

By using a hypothetical example, the magnitude of the nonaction user costs can be easily seen. This example assumes that an asphalt concrete road system is built in 1992. The vehicle operating costs of five types of vehicle (cars, pickup trucks, large cars, trucks, and articulate trucks) are calculated individually for the 1st year and the 20th year, 2011. The international roughness index (IRI) is used to represent the condition of road. An IRI value of 2.2 (good condition) is assigned to the 1st year and a value of 8.8 (poor condition) to the 20th year. A summary of vehicular operating costs of both years is given in Table 1.

The vehicular operating costs in Table 1 are calculated on the basis of 1000 vehicle-km. The daily additional nonaction user costs would be approximately $531 for a section of road identified in poor condition, measuring 1 mi (1.6 km) long, and with the following average working day traffic volumes in both directions:

- Car: 1,800,
- Pickup truck: 1,200,
- Large car: 1,200,
- Truck: 1,200, and
- Articulated truck: 300.

Consequently, the additional nonaction user costs for 200 working days in a year could be as much as $106,000 for a single mile of poor road. The potential accident costs resulting from such poor road conditions are not accounted for here.

#### *Calculation of Action User Costs*

More significant benefits from improving maintenance technology may be achieved by reducing maintenance action–related user costs. The computerized model QUEWZ was developed to estimate the additional user costs resulting from lane closures in one or both directions of travel; it is described by Memmott and Dudek (*2,3*). This program indicates that the length of work zones, the length of closure time, the number of lanes closed, and the traffic volume in both directions affect the amount of user costs extensively.

As with the nonaction user costs, the volume of the action user costs is difficult to calculate unless specific road conditions are detailed. To illustrate the magnitude of the action user costs, a road closure example is developed. In this example, a 1-mi work zone is set up in an urban freeway, and the normal capacity in each direction with two lanes is 4,000 vehicles per hour (vph). When one lane is closed from 8:00 a.m. to 4:00 p.m., the freeway capacity is reduced to 1,800

**TABLE 1 Vehicular Operating Costs Based on HDM-III (In Dollars)**

| | Vehicular Operating Costs of 1000 Vehicle-km ($) | | | | |
|---|---|---|---|---|---|
| Year | Car | Pickup | Truck | L. Cars | Art. Truck |
| 1992 | 136.9 | 127.8 | 140.4 | 488.9 | 774.3 |
| 2011 | 157.4 | 165.0 | 181.5 | 615.6 | 937.1 |
| Difference | 20.5 (15%) | 37.2 (29%) | 41.1 (29%) | 126.7 (26%) | 162.8 (21%) |

vph and the total additional daily user costs due to the lane closure are $17,647. It should be noted that the extra expenditures by road users accounted for in this example exclude the costs of potential accidents and the extra travel time for particular individuals.

From the previous discussion and examples, the magnitude of the impact of maintenance operations on road users is clear. For a given working day, a rough, unmaintained road or a work zone in an urban freeway can cost road users tens of thousands of dollars a day. The costs nationwide are far greater. Automated road maintenance and improved technology could decrease these user costs in many ways.

## BENEFITS OF AUTOMATION IN ROAD MAINTENANCE

Automation is defined in this paper as the replacement of human labor by machinery. Depending on the level of labor replacement, different technology—including mechanical, sensing, computing, actuating, motion, and control systems—applies. Applying automation technology in road maintenance involves the following:

1. Using mechanized systems, such as XY tables and serial manipulators, to replace human labor that involves high strength or simple skills;
2. Using sensors to gather required task-related information from the environment, such as a pothole profile and a crack pattern; and
3. Training maintenance workers to operate the automated system with simple control devices.

Automation technologies have demonstrated tremendous successes in manufacturing and many other industries. In the past 10 years, the construction industry has also shown great interest in automating some of its operations. Numerous benefits could be realized by automating road maintenance.

### Minimizing Work Zones and Interference of Maintenance Operations with Traffic

For most road defect treatment methods, automation would reduce the number of crew carriers, loaders, trucks, and rollers as well as the associated workers because many functions could be combined onto a fewer number of machines. Consequently, the possible interactions between maintenance operations and the traffic could be greatly reduced. Examples include the Dynapac pavement patcher (*5*) and the Thermo-Patch pothole patcher, discussed later (*6*).

In a conventional machine patching job, the equipment involved includes at least one crew carrier, a grader, a roller, and a number of dump trucks. Because the size of a pothole and the level of pothole damage vary, workers and equipment operators need a large work zone to execute the job. As the Dynapac pavement patcher has demonstrated in several field trials, the required work zone space could be reduced significantly.

### Increasing Flexibility of Maintenance Forces

Automation enables crews to perform required maintenance actions at any time of day and under most weather conditions. Working at night has special appeal because the traffic volume is low. With current sensing technologies, such as that on an automated crack sealer (*7*), workers can work without lighting. Often, they do not even need to see, because a sensed image can be processed by central computing units with little human involvement. Under poor weather conditions such as rain, a pothole can be drained, covered, and treated by hot air. Once the humidity in the pothole is within the acceptable level, sensors activate the patching operation (*8,9*).

With automation technology, maintenance tasks generally involve less human labor as demonstrated by the automated crack sealer. This reduction of human labor also increases the flexibility of maintenance forces. When emergency repair is required, for example, machine operators do not have to wait for helpers and flag personnel to start the job. The smaller the crew, the shorter the delay.

### Increasing Capacity of Maintenance Forces

The capacity of maintenance forces determines their responsiveness to a certain road defect once reported. Instead of extensively recruiting, training, and retraining workers and purchasing general purpose equipment such as crew carriers, loaders, and trucks, the capacity of maintenance forces can be expanded with the purchase of multipurpose automated systems. Additionally, if automated systems prove to be more economical than current methods, more capacity can be purchased with the same maintenance budget.

### Improving Quality of Maintenance Operations

Better quality maintenance operations would maximize the time period between road defect treatments. However, quality is often difficult to ensure because of the nature of labor-intensive operations in which experience often plays an important role. Novice workers may not have the knowledge to deal with moisture or hot weather in patching or sealing. In planing or overlaying, the high precision of road curvature or evenness takes much skill and experience to achieve. With various types of sensors, automated systems can perform tasks with the required precision. For example, one new asphalt finisher identified in this study has precise programmable control and internal screed surface pressure and heater temperature sensors (*10*).

### Shortening Operation Time

Because time of road closure has a strong impact on user costs or the action user costs, it is critical to minimize closure time through faster operations. Existing automated systems can facilitate the setup or removal of work zones and accelerate the curing process of paved materials considerably. An example of such a system is the Quick Change moveable barrier system (*11*).

Operation time for the actual defect treatments would also be reduced if manual methods were replaced by mechanized ones that use sensors and electronic control devices. Several potential applications exist in structural treatment of deteriorated roads. Traditionally, maintenance forces practice more surficial treatment methods than structural ones, even when the latter may be required. The reason often has been that structural treatment methods, such as overlays, partial reconstruction, and drainage improvement, take more time. Although no existing system has been identified so far, some existing automated road construction systems, such as automated asphalt finishers (*10*), could be modified for this purpose.

### Reducing Labor Requirements

Because a single automated system can be designed to perform multiple elemental operations, such as mixing patching materials, filling potholes, and screeding patching materials, the number of equipment operators and helpers would be reduced. The amount of labor that could be saved depends heavily on the cognitive complexity of a particular maintenance task. The concept of using human cognition and decision-making capability and replacing human labor by mechanized power makes the labor reduction in many road maintenance tasks possible. In the case of the automated crack sealer, two to three workers may be replaced (*7*). A combination of portable traffic signals (*12*) and radar or laser range sensors would also negate the need for flag personnel.

### Improving Worker Utilization

One of the characteristics in road maintenance is the low-skill nature of manual methods. With automated systems, workers would be more involved in operating machines and monitoring the quality of operations instead of laboring on pavement breakers, shovels, and rakers. Essentially, the new technology employs more human cognitive abilities than physical ones and can improve the image of road maintenance work.

### Conforming to Environmental Regulations

Automated systems can be designed to recycle removed pavement materials, if patching or thin overlay operations are involved. Depending on the required mixture, the operator could instruct the automated system to disintegrate the removed materials, retrieve the desirable ones, and combine them with new materials. To prevent foreign materials or objects from entering the mixing system and ensure the quality of mixture, this process would involve the use of several sensors and some manipulation mechanisms.

### Removing Workers from Danger or Hazards

With automated systems, many manual maintenance methods can be eliminated. Consequently, workers such as flag personnel and shovellers would not be exposed directly to traffic. Reducing even a few accidents a year in this way could result in significant savings. As well, workers could be distanced as far as possible from patching or paving materials, which often cause dermatoses and respiratory problems.

## COSTS OF AUTOMATION IN ROAD MAINTENANCE

Road maintenance automation has five major cost components: (a) research and development (R&D), (b) system procurement, (c) system operation, (d) overhead, and (e) system maintenance. The R&D costs are relevant from a public economic perspective, which is discussed later. The determination of the other four costs is in many aspects similar to that for traditional maintenance methods except for new items such as maintenance of software and electronics. If automation technology is applied to road maintenance, some user training or specialty recruitment in software engineering and electronic devices repair may be required. The parameters affecting each cost component are presented in Table 2.

According to Table 2, some considerations concerning the implementation of automation technology should be high-

**TABLE 2 Parameters of Cost Components**

| Cost Component | Parameters |
|---|---|
| 1. Research and Development | • Management, Administration & Overhead<br>• Salary and Wages<br>• Prototype Systems<br>• Other Permanent Equipment<br>• Development Period |
| 2. System Procurement | • Useful Life<br>• Payment Plan |
| 3. Operating | • System Setup Costs: Transportation, Setup, Dismantle<br>• Labor Costs: Hourly Wages, Work Hours<br>• Energy Costs: Fuel Consumption Rate, Work Hours<br>• Material Costs: Waste Percentage, Unit Material Costs |
| 4. Overhead | • Training<br>• Work Force Re-organization<br>• Safety |
| 5. System Maintenance | • Hardware Component & Labor: Mechanical Systems, Electronic Devices<br>• Software Labor: Updating, Debugging, Modifications |

lighted. Regarding operating costs, the hourly labor wages are expected to be somewhat higher than current ones because operating the automated equipment requires higher skills. The work hours in both the labor and energy items are expected to be shorter because of the increased production. Less material is expected to be used because less material is wasted during operation. Considerable overhead costs may have to be spent on operator training and a worker safety program, and substantial leadership and managerial effort are necessary to reorganize the work force.

## ECONOMICS OF AUTOMATED ROAD MAINTENANCE

To gain insight into the costs and benefits of automation and to derive a comparison between conventional and automated maintenance methods, it is critical to determine the perspective that is taken before any form of analysis is performed. Different perspectives not only affect the determination of costs and benefits but also dictate the time horizon, which is essential in the economic analysis.

From the standpoint of an equipment user, the costs of automated maintenance include the initial capital to purchase a piece of automated equipment and many other items such as labor, costs of energy, and material. The time horizon of the economic analysis is usually within 5 to 10 years. Factors that need to be considered are the potential utility rate, safety concerns during operation, workers' moral, system production rate, crew organization, system robustness, and potential system downtime. If the user is an outside contractor, he or she will also need to forecast the expected market size for a particular type of maintenance job, given the competitive edge of automation technology.

From the perspective of public economy, user benefits and the R&D costs are now also considered, with a planning horizon up to 50 years. The potential reduction of the user costs by the implementation of certain technology becomes a key factor in the economic analysis, with the costs of R&D being treated as a long-term investment to reduce the maintenance operations costs and the user costs.

Other perspectives that can be taken include those of the equipment manufacturers and large construction corporations. An equipment manufacturer will focus on the possibility of creating a larger share of the equipment market by investing in R&D. A large construction corporation is concerned with its competitive edge with respect to other maintenance contractors by investing in R&D. The authors believe that the public economy is the most appropriate perspective for the range of issues to be considered in automated road maintenance.

A formulation for the economic analysis for automated road maintenance is presented in Figures 2 and 3. The balance of these costs and benefits depends on the perspective of the analyst, the accuracy of estimates used, and the time horizon for planning. This paper attempts to make only a limited comparison of the costs and benefits, leaving open the possibility of a more extensive analysis. The following discussion, however, provides some direction of the numbers involved.

From a maintenance force's viewpoint, the benefits are the reduction of the direct costs of maintenance operations, including material, energy, labor, and accident costs. The most important area for cost reduction is in labor costs. If the hourly pay and fringe benefits for a worker are $20, the annual direct costs for employing him or her are $40,000. With automated systems, the labor requirement can be greatly reduced, and significant savings can be realized by reorganizing work crews. The decreased labor requirement introduces the potential for reducing accident costs, because the use of automated systems can eliminate manual operations and minimize the exposure of labor to traffic and hazardous materials. Other benefits to the maintenance forces are the better working conditions and enriched job content supported by the automated systems and the lower overhead due to the reduced number of workers.

From a road user's viewpoint, the benefits are the reductions of the nonaction and the action user costs. For nonaction user costs, minimizing the time lapse between defect formation and repair is essential. A previous example has shown

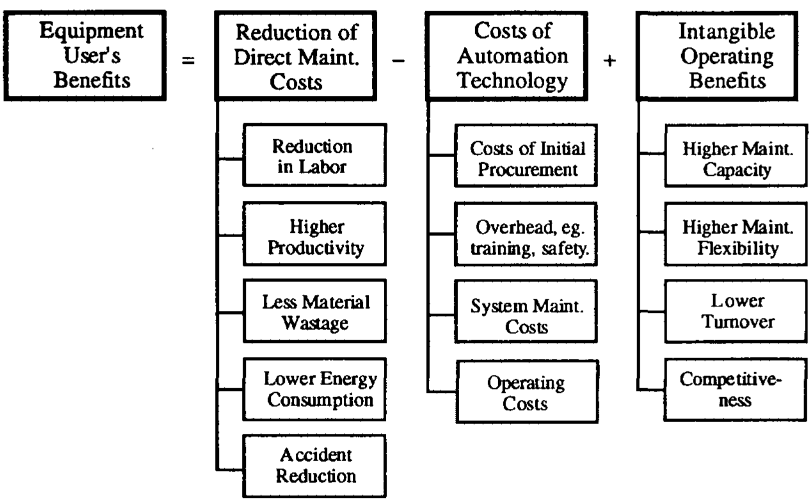


**FIGURE 2 Formulation of economy analysis from equipment user's perspective: 5- to 10-year planning horizon.**

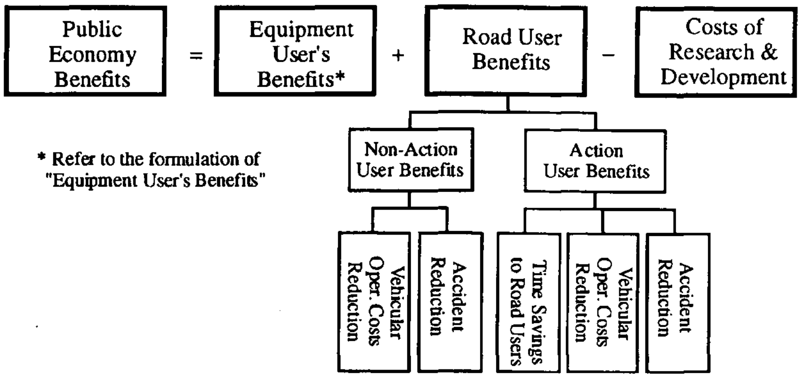


**FIGURE 3 Formulation of economy analysis from public economic perspective: 5- to 10-year planning horizon.**

that poor road serviceability will cost road users, given a relatively low traffic volume, \$531/mi/day. If only 2,000 mi of such roads exist in 50 states, the additional costs of delayed maintenance could exceed \$1 million/day, or close to \$400 million/year. In this respect, the capacity of maintenance forces can be expanded by purchasing more lower-cost automated systems. With limited training, maintenance crews can repair defective roads with automated systems as soon as defects are reported. The user benefits include reducing the number of road defect–related accidents and lowering vehicular operating costs.

To road users, the potential benefits in reducing the action user costs are also high. The most significant benefit is to reduce fuel consumption by eliminating waiting, stop-and-go cycles, and lower travel speeds when passing work zones. In calculating the vehicular operating costs due to a lane closure, a previous example has shown that \$17,647 worth of extra fuel may be burned in vain daily for only one lane closure, not to mention the consequences of air pollution in an urban area. If, among the largest 20 cities in all states, there are on average five such lane closures every day, the additional user costs are approximately \$353 million for 200 working days in a year. Automated maintenance systems can achieve the user benefits by speeding up maintenance operations and reducing the number of lane closures required. These advancements could also limit the travel delays to other individuals in the freeway system (often very significant in urban areas) due to lane closures.

From the perspective of public investment, the costs of R&D in automating road maintenance can be paid with a combination of the operating and user benefits described earlier. As one example, the costs of R&D for an automated crack sealing system has been estimated to be in the range of \$1 million to \$2 million. An economic analysis of the automated crack sealing system shows potential benefits for equipment users of approximately \$3 million annually nationwide (*13*). Because this system is expected to be in service for 6 years, it is clear that, even without considering user benefits, the return on the investment is still potentially high.

The next section describes current advances in road maintenance automation technology. User and operating benefits of these technologies are identified as well.

## AUTOMATION APPLICATIONS IN ROAD MAINTENANCE

A survey on automated applications in road maintenance was conducted in the early stage of this research. As identified in this survey, there are three major categories of automation applications in road maintenance. The first category, which has attracted a considerable amount of research and development, is road defect surveys. The goals of automatic defect surveys are to acquire information about road surface distress quickly, objectively, accurately, and automatically. Such systems can decrease operating costs by reducing labor, and they can lower user costs of manual surveys by operating at highway speeds. Five systems are identified in this study and are given in Table 3.

A second category is traffic control. The goals of automatic traffic control are to ensure communication between maintenance crews and the traffic and to secure the safety of crews while they work under traffic conditions. Because the setup and removal of work zones will affect the total time of road closure, another goal of automatic traffic control is to accelerate the setup and removal of work zones, so that the time of road closure can be minimized. Four systems are identified in this study and are given in Table 4.

A third category is defect treatment. Most automatic systems for defect treatment focus on patching activities. The goals of such systems are to ensure the quality of maintenance operations, to reduce the labor requirement, and to improve the crews' working conditions. These systems are presented in Table 5.

In addition to these three major areas of applications, other systems have been introduced, including an asphalt finisher, an automatic snowplow, a line painting system, a multipurpose traveling vehicle, an automated litter bag retrieval system, and an automated raised marker placement system. A summary of these systems is presented in Table 6.

## SUMMARY AND CONCLUSIONS

Because of increasing maintenance demands and the increasing impact of maintenance operations on users, there is a need

**TABLE 3 Automation Applications in Defect Surveys (*14–22*)**

| System Name | Developer | Description |
|---|---|---|
| Automatic Pavement Distress Survey System | Komatsu Ltd. Japan | Uses laser, video and image processing techniques to measure cracking, rutting and longitudinal profile. Cracks over 1 mm wide can be measured and the survey can be performed at a speed of 60 km per hour. |
| PASCO ROADRECON Systems | PASCO Corporation, Japan | Makes measurements with two longitudinal profilers. Cracking, patching and other distresses can be recorded by a continuous road surface photographic recorder. The vehicle travels at speeds between 5 to 85 km per hour. |
| GERPHO | French Minisere Des Transports | Employs a 35-mm continuously running camera, mounted on a van with a light source that illuminates the pavement. This system takes a continuous image of the pavement surface at speeds up to 64 km per hour. Between 100 to 200 lane kms can be photographed per working night. |
| Automatic Road Analyzer (ARAN) | Highway Products International, Inc. of Paris, Ontario, Canada | 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. Its operating speed is up to 88 km per hour. |
| Laser Road Surface Tester (RST) | Swedish Road and Traffic Research Institute | Measures crack depths and widths, rut depths, longitudinal profile from which roughness is computed, 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 30 to 88 km per hour. |

to improve maintenance technology. By improving maintenance technology, the direct costs of maintenance operations and the related user costs can be reduced. This study focused on automation technology for lowering such costs. Twenty-two automated systems in road maintenance that are used for defect surveys, traffic control, defect treatment, and other supportive activities were identified. These systems demonstrate that automation technology is technically feasible and that it can meet the needs for technological advancements in road maintenance.

Some studies have illustrated that automated maintenance is economically practicable. An economic analysis of crack sealing (*13*) shows that it can save at least $3 million/year nationwide in operation costs. Although the corresponding user benefits were not investigated, they should not be overlooked or underestimated when considering adopting new technologies for road maintenance.

Significant savings can be obtained by shortening the lane closure time and minimizing the size of a work zone. It was estimated earlier that road users spend more than $300 million nationwide on extra fuel consumption alone for passing work zones every year. If, with the introduction of automated systems, the operation time and number of lane closures were reduced by 10 percent, the United States could realize fuel savings annually of $30 million or more. A near–traffic speed asphalt finisher and the Quick Change moveable barrier system show promise in this regard.

Significant user benefits could also be attained by shortening the time lapse between defect formation and repair. Clearly, increasing the capacity of maintenance forces would help do this, provided that road surveys report timely defect information. Automated systems that do reduce operations costs will allow agencies with limited budgets to expand their capacity. The resulting user benefits could approach many millions of dollars a year.

The major conclusions of this study are as follows:

1. Automation in road maintenance is technically feasible in some areas and can pay for itself.
2. Reducing the labor employment in road maintenance is a key issue in decreasing the direct costs of maintenance operations.

**TABLE 4 Automation Applications in Traffic Control (*11,12,23–25*)**

| System Name | Developer | Description |
|---|---|---|
| Addco Cone | Addco Manufacturing Co. Minnesota, USA | 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 much faster. |
| Quickchange Movable Barrier System | US Barrier Systems, Inc., California, USA | Consists of a 3-km chain of 636 kg hinged concrete sections and a machine to place and retrieve the barriers. The machine lifts each barrier off the surface, transports it on a large conveyor belt, and accurately repositions the barrier on its new lane location. The entire operation is 25 to 30 minutes. |
| Super Quartz II Portable Traffic Signals | Horizon Signal, Pennsylvania, USA | Makes it possible for highway crews to automatically control traffic flow by way of a series of microprocessor-controlled, battery-powered signals. Up to 16 traffic lights can be controlled from a single, user-programmed micro-terminal. It can continue to operate using one fully charged 12 volt battery for 72 hours. |
| Remote Controlled "Follower" | Minnesota Department of Transportation, USA | Consists of a large heavy truck which can be operated from a safe distance by a semi-skilled operator. The truck follows the crew slowly (approximately 8 km per hour) and the operator can control the steering and speed of forward motion. It can be fitted with signals alerting the public, as well as cushions to lessen the damage from a collision. |

TABLE 5 Automation Applications in Defect Treatment (5–9,26–29)

| System Name | Developer | Description |
|---|---|---|
| Dynapac Pavement Patcher | Dynapac Light Equipment, New Jersey, USA | Capable of spraying emulsion, spreading aggregate and compacting the mixture all in one pass. It can be adjusted to various widths from 0.3 to 2.1 m in 0.3 increments, and any spray pattern can be achieved including multiple parallel patches. |
| Thermo-Patch Pothole Patcher | Northwestern U. & UC Davis, USA | Brings several different components together and is properly sized to adequately perform the task without material waste. |
| "Puff" the Pothole Patcher | One Man Inc., New Mexico, USA | 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 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. |
| Automatic Crack-Filling Robot | Carnegie-Mellon U. and U of Texas at Austin, USA | Integrates a video-based raster scan image with a laser range sensor that supplies information about the third dimension. The repair process is performed by an x-y table with three mounted tools: a heated air torch, a sealing wand and the infrared laser range sensor. |
| Robotic Crack Sealing System | California Department of Transportation and U. of California at Davis, USA | The equipment under development utilizes a machine vision system to identify the cracks while a robot manipulator prepares and seals the cracks. The automated machine will prepare and seal both longitudinal and transverse cracks. |
| Asphalt Paver | Barber Greene Equipment Co., USA | It features large, wide-inlet self-dumping hoppers, high capacity long-lift feeder and spreading auger systems. Fully hydrostatic drive systems provide a smooth efficient operation with a capacity to handle varying paving requirements. Automatic control systems provide fully proportional control of the material feed to match job requirements. |
| Hot Mix Paver | Cedarapids Equipment Co., USA | Standard features include three-point suspension, full lighting package, high alloy slat liners, power-adjustable hopper gates, dual-position swing console and the standard 8 foot Fastach screed to deliver the suspension performance needed to produce a quality mat. |

3. A major emphasis of R&D for automation in road maintenance should be placed on minimizing user costs in addition to reducing the direct costs of maintenance operations.

4. As the QUEWZ model shows, to reduce the action user costs, the R&D effort should focus on shortening the required operation time and the size of work zones.

5. As the HDM-III model shows, to reduce the nonaction user costs, the R&D effort should focus 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. The demand for road maintenance will increase rapidly over the upcoming years. Maintenance forces around this country must respond to this need by improving maintenance efficiency through automation technology.

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TABLE 6 Automation Applications in Supportive Activities (29–33)

| System Name | Developer | Description |
|---|---|---|
| Asphalt Finisher | Nippon Hodo Co., Ltd., Japan | Has a liquid crystal color display, a touch panel, voice response, etc. for ease of operation. The screed surface pressure and heater temperature can be changed freely and the range of paving materials that can be used is wider than an ordinary asphalt finisher. |
| Automatic Snowplow | Nichijo Manufacturing Co., Japan | Consists of the steering operation unit, the operation panel, the control unit, the hydraulic unit, the ferrite sensor unit, and the steering actuator unit. XY control, concentration control, linear motion control and pattern control in chute operations for snow throwing and driving control for steering operations are provided. |
| Automatic Line Painting System | Ministry of Transportation of Ontario, Canada | Increases the speed and accuracy of the operation while decreasing the demands placed on the driver. 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. |
| Multipurpose Traveling Vehicle | Societe Nicholas of France | 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. |
| Automatic Litter Bag Retrieval System | California Department of Transportation and U. of California at Davis, USA | Utilizing a single operator, this prototype will automatically pick up litter filled bags from the highway right of way while in motion. Future generations of this machine will have the potential to remove unbagged litter and debris. |
| Automated Raised Marker Placement System | California Department of Transportation and U. of California at Davis, USA | The current development will allow higher speeds of dispensing of adhesive and various types of RPMs by a single operator. One such device will place RPM s on newly paved roadways while another machine under development will replace missing RPMs on previously marked pavement with speeds up to 10 miles an hour. |

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