California AHMCT Research Center
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ROBOTIC MAINTENANCE AND CONSTRUCTION
FOR AUTOMATED HIGHWAY SYSTEMS:

ECONOMIC ANALYSIS

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ABSTRACT

The cost of congestion on major highways has become very high indicating the need for increased highway capacity and resulting in the conceptual development of automated highway systems. Although much research is ongoing concerning the manner in which automated highways should operate and how they should be implemented, there has been minimal investigation concerning construction and maintenance requirements. As the demand and performance of the highway increases, the impact of maintenance and construction operations will in turn be more dramatic. Therefore, the need for improved maintenance and construction techniques is vital to the success of the high capacity AHS.

As existing highway systems deteriorate, labor costs have increased, resulting in the need and development of more efficient and safer highway maintenance techniques using automation and robotics. Automated systems have been successfully developed to perform various maintenance tasks such as crack sealing. Research in the field of automated road maintenance and construction has shown that there is significant potential for cost saving due to increased efficiency, increased safety, and less traffic delays.

The costs and benefits of robotic construction and maintenance for automated highway systems is investigated in this thesis. The analysis considers the direct costs to the transportation agency or contractor and the user costs to the driving public. Direct costs are associated with equipment, labor, and material costs. User costs are due to increased traffic congestion resulting from highway maintenance operations. A computer model was developed to quantify the benefits associated with the automation of a particular maintenance task. Case studies of magnetic markers installation and pavement repairs were performed and results are given.

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FOREWORD

The cost of congestion on major highways has become very high indicating the need for increased highway capacity and resulting in the conceptual development of automated highway systems. Although much research is ongoing concerning the manner in which automated highways should operate and how they should be implemented, there has been minimal investigation concerning construction and maintenance requirements. As the demand and performance of the highway increases, the impact of maintenance and construction operations will in turn be more dramatic. Therefore, the need for improved maintenance and construction techniques is vital to the success of the high capacity AHS.

As existing highway systems deteriorate, labor costs have increased, resulting in the need and development of more efficient and safer highway maintenance techniques using automation and robotics. Automated systems have been successfully developed to perform various maintenance tasks such as crack sealing. Research in the field of automated road maintenance and construction has shown that there is significant potential for cost saving due to increased efficiency, increased safety, and less traffic delays.

A model to estimate the cost benefits of robotic construction and maintenance for automated highway systems is developed in this report. The analysis considers the direct costs to the transportation agency or contractor and the user costs to the driving public. Direct costs are associated with equipment, labor, and material costs. User costs are due to increased traffic congestion resulting from highway maintenance operations. The computer model was developed to quantify the benefits associated with the automation of a particular maintenance task. Case studies of magnetic markers installation and pavement repairs were performed and results are given.

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a   - Intercept term for work zone capacity equation.
ACUM   - The average number of accumulated vehicles in a queue.
AOCM   - Annual operating cost for the manual method.
AOCR   - Annual operating cost for the robotic method.
AOCS   - Annual operating cost savings.
AUCR   - Annual user costs for the robotic method.
b   - Slope term for work zone capacity equation.
C   - Highway capacity.
CAPW   - Restricted capacity during work zone activity hours.
CDSC   - The delay cost of a speed change cycle.
CDWZ   - The dollar delay cost of going through the work zone at reduced speed.
CERF   - Capacity estimate risk factor.
CL   - Estimated Cost of Life (Federal Highway Administration).
CLL   - Effective length of closure.
CQUE   - Cost of queue delay.
CSPC   - Additional operating cost of a speed change cycle.
CSPQ   - Additional speed-change operating cost with a queue.
CUF   - Factor to update cost calculations.
C_{wz} - Capacity of work zone.
D   - The probability of death occurrence during this operation per year on statewide basis.
DQUE   - The average delay for each hour a queue is present.
DSC   - Distance traveled during a speed change cycle.
DUC   - Daily user costs.
EF   - The gain in productivity efficiency.
EOC   - Manual equipment operating cost in dollars per hour.
HPD   - The number of working hours per day.
L   - Economic life of the robot in years.
LSAV   - Life Savings.
MARR   - Minimum attractive rate of return.
MC   - Material usage cost for the manual method.
MCR   - The gain in material usage efficiency for the robotic method.
NOFW   - Number of workers required for the manual method.
NOFWR   - Number of workers required for the robotic method.
OC   - The change in vehicle running costs.
OCQ   - The change in vehicle operating costs when a queue is present.
ODY   - Operating days per year.
P   - Present value of a future amount.
PCT   - Percentage of cars on the highway.
PQUE   - The percentage of the hour that a queue is present.
PTT   - The percentage of trucks on the highway.
QUEL   - Average length of the queue in kilometers.
$QVOC_c$ - The change in vehicle operating costs for a car when a queue is present.
$QVOC_t$ - The change in vehicle operating costs for a truck when a queue is present.
R   - Risk factor, the level of exposure to traffic relative to other maintenance operations.
ROC   - The operating cost of the robot including energy and wear and tear costs.
S   - Annual savings resulting from the robot.
SP   - Average vehicle speed.
SP_1 - Parameter for the estimation of average speed, default value = 97 km/h.
SP_2 - Parameter for the estimation of average speed, default value = 64 km/h.

SP_3 - Parameter for the estimation of average speed, default value = 48 km/h.

SP_{ap} - Approach speed.

SPCC   - The change in vehicle operating costs resulting from speed change cycles for cars.

SPCT   - The change in vehicle operating costs resulting from speed change cycles for trucks.

SP_{mn} - Minimum speed of vehicles through the work zone.

SP_q - The average speed through the queue.

SP_{wz} - Average speed through the work zone.

THC   - Total hourly user costs.

TL   - Total number of lanes upstream of the work zone.

V   - Average traffic volume.

V1   - Volume parameter for the estimation of average speed, default value = 2000 vehicles per hour per lane.

V2   - Volume parameter for the estimation of average speed, default value = 1600 vehicles per hour per lane.

VLT_C - Value of time for cars in dollars per hour.

VLT_t - Value of time for trucks in dollars per hour.

VOC_c - The change in vehicle running costs for a car.

VOC_t - The change in vehicle running costs for a truck.

WAGE   - The wage paid to manual operation workers in dollars per hour.

WAGER   - The wage paid to robotic operation workers in dollars per hour.

WZD   - Length of restricted capacity around work zone in kilometers.

Chapter 1
Introduction

Traffic congestion is a major problem with today's transportation system. Currently, over 70 percent of all rush-hour traffic on major highways is heavily congested; this is expected to be over 80 percent by the year 2000 (Stevens, 1993).[11] Freeway systems have proven to be an effective mass transit system. However, the demand on our freeways is increasing faster than new lanes can be built. A new approach to increasing capacity is the Automated Highway System (AHS). The AHS has the potential to greatly increase the amount of people, goods, and vehicles that can travel on existing highway right-of-ways. The AHS will increase capacity by (1) increasing speed; (2) increasing density; (3) increasing the number of lanes that will fit on the same right-of-way; and (4) eliminating those characteristics of drivers that inhibit traffic flow (Stevens, 1993).[11]

AHS refers to the use of automatic control to replace some of the human functions of driving. The advantage of an AHS is that vehicles can be spaced closer together both longitudinally and laterally due to the significantly reduced reaction time with corresponding higher attention level of computer control. AHS is presently at the conceptualization stage with many possible system configurations.

The most advanced scenario would use both longitudinal and lateral vehicle control along with lane merging and platooning capabilities. A more simplified approach may use only longitudinal control leaving steering to the driver. Despite these differences, a common objective of almost all AHS configurations is to improve the performance of our present highway system. Performance is expressed using terms such as: average speed, volume to capacity ratio (V/C), vehicle hours traveled (VHT), vehicle miles traveled (VMT), vehicle hours of delay (VHD), and safety. Each of these parameters can be adversely affected by highway maintenance and construction operations. As the demand and performance of the highway increases, the impact of maintenance and construction operations will in turn be more dramatic. Therefore, the need for improved maintenance and construction techniques is vital to the success of the high capacity AHS.

Literature Search

A literature search was performed to investigate existing economic studies of AHS maintenance and construction. Infrastructure systems and possible AHS scenarios have been presented in Lasky and Ravani (1994), Hall and Tsao (1993), and Martin Marietta (1993).[6,4,15] The effectiveness of an automated lane on freeway operations has been examined in Smith (1993).[10] Although much research is ongoing concerning the manner in which automated highways should operate and how they should be implemented, there has been minimal investigation concerning construction and maintenance requirements. However, there has been previous research and development for the automation of road construction and maintenance equipment applied to normal highways. For example, Skibniewski and Hendrickson (1990) have noted that road construction and maintenance works have a significant potential for gradual automation of their individual tasks, due to their repetitiveness and relatively moderate sensory requirements in comparison with other construction tasks.[9] Research by Hsieh and Haas (1993) concludes that there is a need to improve road maintenance technology, and that by improving maintenance technology, the direct costs of maintenance operations and the related user costs can be reduced.[5] For example, the annual operational cost savings for an automated crack sealing machine has been estimated to be $275,000 (Velinsky, 1993).[12] The Advanced Highway Maintenance and Construction Technology (AHMCT) Center at the University of California at Davis has studied many possible robotic and automated highway maintenance systems. AHMCT has built prototype machines for the automation of various highway maintenance tasks including raised pavement marker installation, crack sealing (Velinsky, 1993), hazardous spill pickup, and

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stenciling (Broverman, 1993).[12,11] Although it has been shown that there is a need to improve road maintenance technology, and that road construction and maintenance works have a significant potential for automation, it is the author's opinion that the cost benefits of automated maintenance and construction has not been investigated for the case of automated highway systems. The road user costs at work zones has been investigated by Memmott and Dudek (1982) and a computer model called QUEWZ was developed to quantify the delay costs associated with highway work zone operations.[7] Vehicle delay during maintenance or reconstruction activity of two-lane highways has been investigated by Cassidy and Rowowsky (1993).[2] An engineering and economic analysis of robotics application in potential in selected construction operations has been performed by Skibniewsky (1986).[8] The time value of money method which is used for determining the value of a proposed robotic system is explained by Dorf (1988).[3]

Problem Statement and Objective

This report builds upon previous research for robotic maintenance and construction of highways and extends it to the AHS case. The impact of maintenance operations on automated highway systems will be investigated and a method for quantifying the value of a proposed maintenance robot will be developed.

Chapter 2 outlines the method by which this cost benefit analysis will be accomplished. A review of literature in the field of AHS hardware and operation is given and the concept of user costs and direct costs is introduced.

In Chapter 3, a cost benefit computer model is presented. Given data concerning automation of a possible maintenance task and/or road closure scenario the model will calculate annual user and direct cost savings. Using the time value of money method the model can then determine the value of automating the given task. Calculations for the model are described and user instructions are given.

Chapter 4 develops two case studies. The first case investigates the installation of discrete magnetic markers which are used for automatic vehicle control. The second case investigates pavement surface repairs. For each case, a manual method is compared with an equivalent robotic method. Problem formulation and results are presented.

Finally, in Chapter 5, conclusions and benefits from the work are summarized, and recommendations are made for future work.

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Chapter 2
Methods for Analysis

An engineering economic analysis is a systematic examination of complex investment activity that provides a basis for making a decision with respect to capital investment. In general, there are two situations for which an economic analysis is used. The first situation involves investment in equipment for a new application; the second involves an investment to replace an existing method (Skibniewski, 1986).[8]

In the first case, the purpose of the analysis is to identify the least expensive method with which to accomplish a given task. The second case is to provide a quantitative comparison of the present method and one or more new methods. The task of evaluation in the second case becomes difficult because it is based on investment cost compared to savings over the operating costs of an existing method (Skibniewski, 1986).[8] This study can be categorized as an analysis of a robotic alternative to already existing construction and maintenance methods which may be applied to automated highways.

For this analysis the costs of AHS maintenance and construction have been categorized into two separate components: direct costs and user costs. The direct costs associated with a maintenance operation are those costs which will be directly incurred without considering costs associated with restricting traffic flow. These costs include labor, equipment, and material costs. The cost of maintaining the infrastructure of an automated highway is dependent upon the degree to which automation functions are incorporated into the infrastructure. Possible AHS scenarios range from control systems which are completely contained within the vehicle to those in which the roadway contains all of the control hardware. At a minimum, the direct cost of maintaining an automated highway will be the same as present highway systems. As more automation functions are shifted from the vehicle to the highway infrastructure, the cost of maintenance grows. For example, the infrastructure of an automated highway system could possibly include some combination of the following components: active lane markers such as embedded guidance wire; passive center lane markers such as magnets; passive barriers and/or markers on the side of each lane; (Stevens, 1993).[11] Accordingly, functions will be associated with the maintenance of each of these components beginning with installation, then periodic inspection and preventative maintenance. A more detailed list of infrastructure systems and possible AHS scenarios can be found in Lasky and Ravani (1994), Hall and Tsao (1993), and Martin Marietta (1993).[6,4,15]

In addition to the direct operational costs of AHS maintenance discussed above, the total cost of AHS maintenance will include substantial user costs. When the capacity of an AHS lane(s) is reduced or eliminated due to maintenance operations, it is likely that the overflow traffic will be switched to manual mode through the work zone. The user costs associated with manual driving through work zones can be grouped into four general categories: delay or travel time costs, vehicle running costs, speed-change cycling costs, and accident costs. Delay costs result from reduced speed through the work zone, delay in slowing down from and returning to the approach speed, and delay in a queue if demand exceeds capacity. Changes in vehicle operating costs result from reduced speeds through the work zone and queue, if any. Speed change cycling costs are generated from slowing down to go through the work zone and stop-and-go conditions if a queue is present. Changes in user accident costs are difficult to quantify due to the lack of data related to changes in accident rates through a typical work zone (Memmott and Dudek, 1982).[7]

To determine the overall cost benefits of robotic maintenance of an AHS, both direct and user costs will be considered. By comparing the costs of a manual method and a robotic method, the annual cost savings will be determined. Using the time value of money method, it is then possible to determine the overall value of a proposed automation project or robot.

In general there are two reasons for the estimation of the net present value of a robot: (1) To determine the attractiveness of the investment in its development and serial production (from the developer's viewpoint); and (2) To determine the attractiveness of its purchase

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(from a contractor's viewpoint) (Skibniewski, 1986).[8]   The net present value is the current value of the robot if the gains in future years are converted to the amount of money that, if invested at the required rate of return, would give the same amount of cash at that future date (Dorf, 1988).[3]   Net present value is a function of the savings provided by the robot, the interest rate, and the life of the robot. For this study a variation of the net present value called the 'Break Even' value will be computed. The 'Break Even' value is the same as the net present value except that the initial cost of the robot is not deducted. This is a threshold value assigned to the robot, above which the machine would no longer be profitable under the given operational assumptions. First it will be computed based on direct cost savings. Secondly, it will be computed based on user and direct cost savings combined. The combined 'Break Even' value represents the value of the automation project to both the contractor and to the driving public.

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Chapter 3
The Cost-Benefit Model

Considering the relatively early state of research into highway automation and the enormous uncertainty and variability in actual deployment approaches, it is difficult to make estimates for the construction and maintenance requirements of future automated highway systems. However as the concepts evolve and maintenance requirements are defined, this model provides a framework for determining the overall cost savings of robotic AHS maintenance. The model uses a computer program called Demos[1]. Demos was also used by Rockwell International for the PATH Research Report entitled "Potential Payoffs from IVHS: A Framework for Analysis, Appendix C".[14] Demos is designed for economic modeling applications. It incorporates a graphical interface making its use simple. The developed model is intended to be used for evaluation of one specific maintenance function at a time, i.e., crack sealing, pothole repair or magnetic marker installation. However, the framework of the model can accommodate a wide variety of possible maintenance scenarios and highway closure strategies. Input data for the model requires some detailed knowledge including time estimates and labor requirements for the proposed automated method and the manual method. Also, for each maintenance function, the model will calculate the direct and user cost savings for both a manual method and an equivalent robotic method. As noted earlier, direct costs represent equipment, labor, and material costs. User costs represent the cost of traffic congestion resulting from highway maintenance acivity.

Direct Costs Submodel

This submodel will calculate the direct cost of AHS maintenance. Method I corresponds to the manual method and Method II corresponds to the robotic method. Input and output data for the direct costs submodel includes:

Input Data:

Method I

1. Number of Workers Required
2. Equipment Operating Cost
3. Material Cost
4. Operating Days/Year

Method II

1. Number of Workers Required
2. Robot Operating Cost
3. Material Cost/Savings
4. Initial Cost of Robot
5. Economic Life of Robot
6. Minimum Attractive Rate of Return
7. Life Savings Ratio
8. Efficiency Factor

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[1] Lumina Decision Systems, Inc.

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Output Data:

1. Annual Labor Cost Savings
2. Annual Life Savings
3. Total Daily Direct Maintenance Cost savings
4. Direct Break Even Value of Robot

User Costs Submodel

The model calculates the user costs that would result when an AHS lane(s) is shut down or traffic flow is restricted to some degree. The basic theory for user costs associated with highway maintenance operations has been previously developed by Memmott and Dudek (1982), and this work extends their theory to AHS applications. The interested reader is thus referred to Memmott and Dudek (1982) for detailed derivations of the theory.[7] Traffic flow through a work zone is dynamically simulated within the model so that delay and vehicle operating costs can be calculated. The input and output data of the user costs submodel includes:

Input Data:

1. Total Number of Lanes
2. Number of Open Lanes
3. Length of Closure
4. Time of Closure
5. Traffic Volumes by Hour
6. Capacity of Work Zone by Hour
6. Percentage of Trucks
7. Value of Time (cars & trucks)

Output Data:

1. Vehicle Capacity
2. Average Speed Through Work Zone
3. Average Length of Queue for each Hour
4. Annual User Cost Savings

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Direct Cost Calculations

The direct operating costs of performing a maintenance task are primarily composed of labor costs, equipment operating costs, and material costs. The following equation is used to estimate the annual operating cost for the manual method (AOCM):

$$AOCM = ODY \bullet (HPD \bullet (WAGE \bullet NOFW + EOC) + MC) \qquad (1)$$

where
- ODY = operating days per year,
- HPD = operating hours per day,
- WAGE = wage for manual operation worker ($/hr),
- NOFW = number of workers required,
- EOC = equipment operating cost ($/hr), and
- MC = material cost ($/day).

The calculation of the annual operating cost for the robotic method is similar to the above calculation for the manual method except for the following modifications. The equipment operating cost (EOC) is replaced with the robot operating cost (ROC). There is an additional factor in case there is a gain in material usage efficiency (MCR). The number of workers for the robotic method (NOWR) and the wage (WAGER) for the robotic method is allowed to be different than for the manual method. For the robotic method an adjustment must be made to ODY since a robotic system can usually provide an increase in productivity over a manual operation. The increase in time efficiency (EF) is used to account for the increase in productivity,

$$EF = \frac{T_m - T_r}{T_m} \bullet 100\% \qquad (2)$$

where
- T_m = Time required to perform the task manually, and
- T_r = Time required to perform the task using the robotic method.

The following equation is used to estimate the annual operating cost for the robotic method (AOCR):

$$AOCR =$$

$$ODY \bullet \left(\left(1 - \frac{EF}{100}\right) \bullet HPD \bullet (WAGER \bullet NOWR + ROC) + \left(1 - \frac{MCR}{100}\right) \bullet MC \right) \qquad (3)$$

where
- EF = gain in time efficiency (%),
- WAGER = wage for robotic operation worker ($/hr),
- NOWR = number of workers for the robotic operation,
- ROC = robot operating cost ($/hr), and
- MCR = gain in material usage efficiency (%).

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The annual operating cost savings (AOCS) is equal to the difference between the operating cost for the manual method and the operating cost for the robotic method, written as

$$AOCS = AOCM - AOCR. \qquad (4)$$

The life savings associated with employing a robotic method which removes maintenance workers from the dangers of the roadway has been derived by Caltrans. The following is used to estimate life savings:

$$LSAV = B \times C \times D \times E \qquad (5)$$

where

B = % per year Savings / Increased Efficiency,
C = The probability of death occurrence during this operation per year on statewide basis,
D = Risk factor, the level of exposure during this operation relative to other maintenance operations, and
E = Estimated Cost of Life (Federal Highway Administration).

User Costs Calculations

The calculation of user costs in this model is patterned after the work of Memmott and Dudek (1982) . The user costs submodel is basically a Demos version of their FORTRAN program QUEWZ. The following equations, tables, and graphs were obtained from Memmott and Dudek (1982) and are intended to be used for regular highway situations. However, they are used for this application with the assumption that the displaced traffic volume due to the closure of an automated lane will be switched to manual operation. This section is provided for completeness, and the intersed reader is referred to Memmott and Dudek (1982) for greater details about QUEWZ.[7]

Estimation of Vehicle Capacity Through a Work Zone

The model assumes that capacity under normal conditions is 2000 vehicles/hr/lane (vphpl). To be effective well into the 21st century, automated highway technology must theoretically improve freeway lane capacity by 2 to 4 times the current capacity (Vostrez, 1989).[13] Therefore, the model assumes that normal AHS lane capacity will be 4000 vphpl. When lanes are closed for prolonged periods, but work activity is not taking place in the work zone, the capacity of manual lanes is taken to be 1800 vphpl, or about 90% of normal capacity. The following figure is from Memmott and Dudek (1982) and can be used to estimate the capacity of a work zone for given closure situations.[7] The numbers in the parentheses indicate the number of original lanes and the number of open lanes through the work zone. The capacity estimate risk factor is the probability that the estimated capacity will be less than or equal to the actual capacity. The figure identifies the risks in using certain capacity values for a given lane closure situation. For example, the 80th percentile for the (2,1) situation is 1290 vphpl. This means that in 80% of the studies, the traffic volume was greater than or equal to 1290 vphpl. Work zone capacity (CAPW) values are part of the input data for the model. CAPW is a 24 element array into which capacity values must be entered for each hour of the day.

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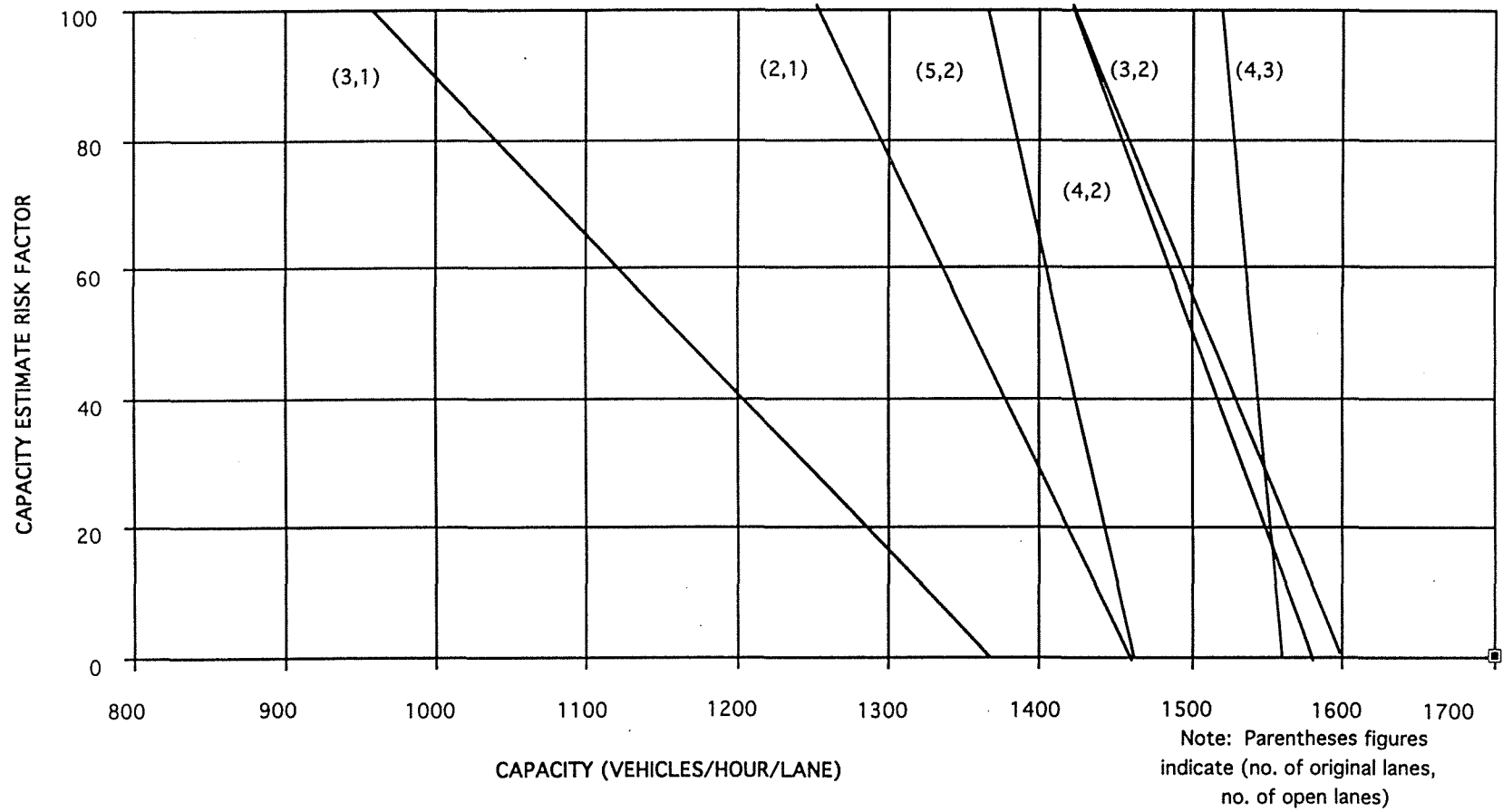
Figure 1. Cumulative distribution of work zone capacities.

The following equation and data were derived through regression analyses of the capacity data through work zones in order to extend the closure possibilities of figure 1:

$$CAPW = a - b(CERF) \ . \tag{6}$$

where
CAPW = restricted capacity during work zone activity hours, and
CERF = capacity estimate risk factor.

Table 1. Restricted capacity coefficients.

Normal Number of Open Lanes in One Direction	Open Lanes Through Work Zone in One Direction				
	Intercept Term (a)				
	1	2	3	4	5
2	1460				
3	1370	1600			
4	1200	1580	1560		
5	1200	1460	1500	1550	
6	1200	1400	1500	1550	1580

	Slope Term (b)				
	1	2	3	4	5
2	2.13				
3	4.05	1.81			
4	0.00	1.60	0.57		
5	0.00	1.46	0.00	0.00	
6	0.00	0.00	0.00	0.00	

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Average Speeds Calculation

The speed of vehicles approaching the work zone is assumed to follow the speed-volume curve given in figure 2. Truck speeds are assumed to be 90 percent of car speeds. The three speed parameters, SP_1, SP_2, and SP_3; and the volume parameters, V_1, and V_2; have preset constant values or default values if the user does not specify speed and volume parameters. These are the same default vaules used by Memmot and Dudek (1982).[7] Those default values are:

$$SP_1 = 97 \text{ km/hr (60 mph)},$$
$$SP_2 = 64 \text{ km/hr (40 mph)},$$
$$SP_3 = 48 \text{ km/hr (30 mph)},$$
$$V_1 = 2000 \text{ vphpl, and}$$
$$V_2 = 1600 \text{ vphpl}.$$

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VEHICLES PER HOUR PER LANE
or V/C RATIO
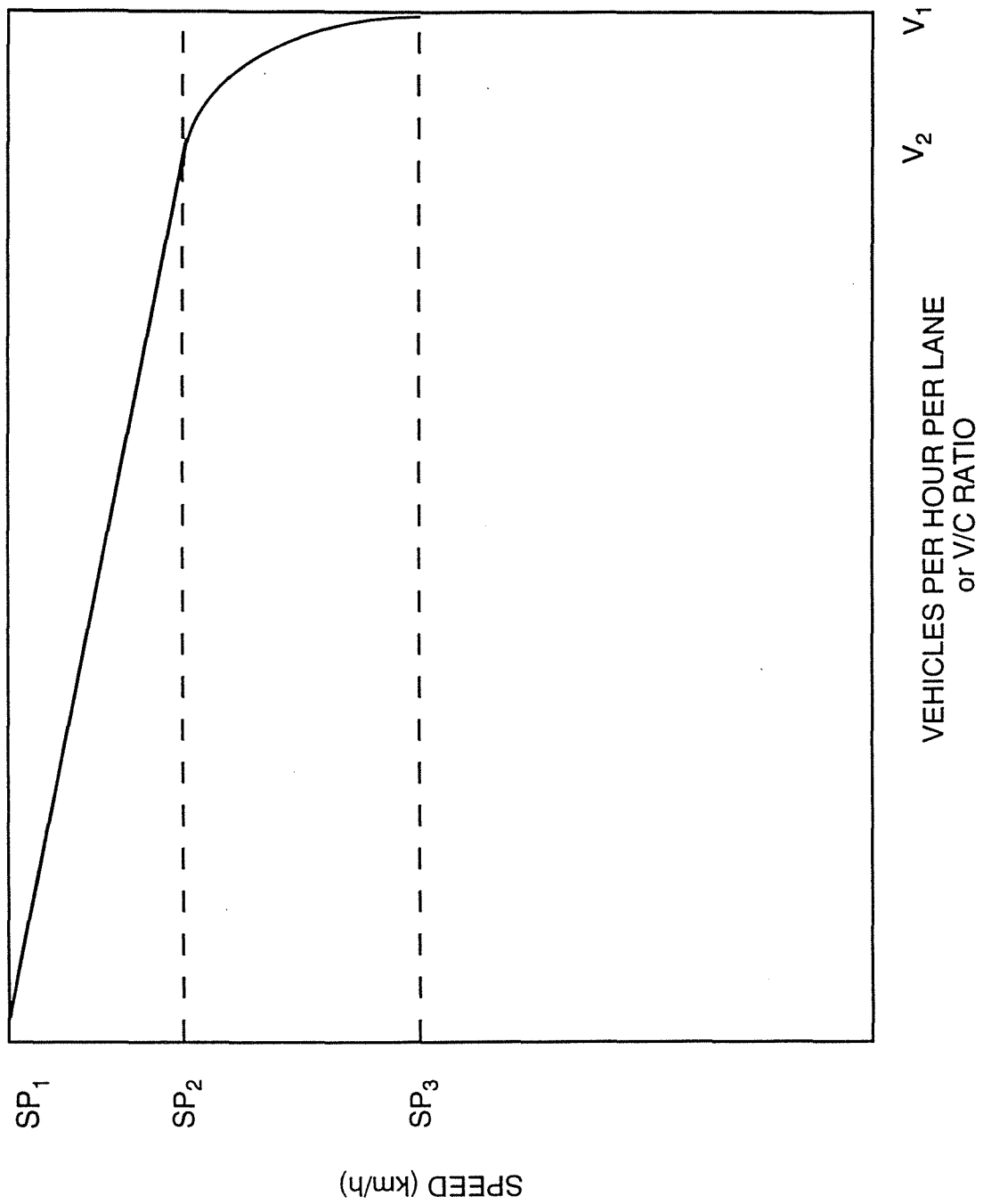
Figure 2. Hourly speed-volume curve.

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Table 2 gives some additional values for speed-volume parameters. The parameters vary by the number of freeway lanes and the peak-hour factor, which is the ratio of the peak-hour traffic volume and the maximum 5-min. rate of flow within the peak-hour. A peak-hour factor of 0.91 is recommended for large metropolitan areas over a million population, a peak-hour factor of 0.83 for areas between 500,000 and 1,000,000 population, and a peak-hour factor of 0.77 for areas under 500,000 population (Memmott and Dudek, 1982).[7]

Table 2. Recommended speeds and volumes for freeways of various lanes and peak-hour factors.

	Peak Hour Factor			
4 lanes	1.00	0.91	0.83	0.77
SP_1	97	97	97	97
SP_2	59	61	65	68
SP_3	48	48	48	48
VL_2	1800	1650	1500	1400
VL_1	2000	2000	2000	2000
6 lanes				
SP_1	97	97	97	97
SP_2	59	63	65	69
SP_3	48	48	48	48
VL_2	1800	1650	1500	1400
VL_1	2000	2000	2000	2000
8 lanes				
SP_1	97	97	97	97
SP_2	59	63	65	69
SP_3	48	48	48	48
VL_2	1800	1650	1500	1400
VL_1	2000	2000	2000	2000

Within the model hourly traffic volume is specified as a 24 element array and must be specified by the user. Using the values specified by the user the following equations give the approach speed. These equations are based on the speed-volume relationship of figure 2 which can be customized using table 2.

if $\frac{V_2}{V_1} \geq \frac{V}{C}$, then

$$SP = SP_1 + \frac{V_1(SP_2 - SP_1)}{V_2} \bullet (V/C) \tag{7}$$

if $\frac{V_2}{V_1} > \frac{V}{C} \leq 1$, then

$$SP = SP_2 + (SP_2 - SP_3)[1 - (\frac{\frac{V}{C} - \frac{V_2}{V_1}}{1 - \frac{V_2}{V_1}})^2]^{\frac{1}{2}} \tag{8}$$

if $\frac{V}{C} > 1$ or a queue is present, then

$$SP = SP_3(2 - \frac{V}{C}), \text{ with the speed constrained to the following range,} \tag{9}$$
$$32 \leq SP \leq SP_3.$$

The average speed through the work zone (SP_{wz}) is calculated from the same speed equations above, using the V/C ratio of the work zone area.

The minimum speed of vehicles through the work zone is somewhat lower than the average speed through the work zone, and can be estimated using the V/C ratio of the work zone as

$$SP_{mn} = SP_{wz} - 3.7 - 41.4(\frac{V}{C_{wz}})^2. \tag{10}$$

If there is a queue, then $SP_{mn} = 0$.

Calculation of Delay Through the Lane Closure Section

Since the distance over which vehicles slow down through a work zone is not always the entire distance of restricted capacity, the following equations are used to estimate the effective length of closure (CLL), in kilometers of reduced average speeds:

$$CLL = 0.16 + (WZD + 0.61)(\frac{V}{C_{wz}}) \tag{11}$$

where WZD = length of restricted capacity around work zone, in kilometers.

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if $WZD \leq 0.16$, or if $V / C_{wz} > 1.61$, then

$$CLL = WZD + 0.322.$$ (12)

If the work zone closure is less than 0.16 kilometers, then the model assumes traffic will slow down through the entire work zone.

The dollar delay cost of going through the work zone at reduced speed (CDWZ), is calculated as,

$$CDWZ = (CLL)(\frac{1}{SP_{wz}} - \frac{1}{SP_{ap}})(V)(CUF)(PTC \bullet VLT_c + \frac{PTT \bullet VLT_t}{0.9})$$ (13)

where
SP_{ap} = approach speed (km/h),
VL = hourly vehicle volume (vph),
CUF = cost update factor,
PCT = percentage cars $\div 100$,
PTT = percentage trucks $\div 100$,
LT_c = car value of time ($/hr.), and
VLT_t = truck value of time ($/hr.).

Calculation of Queue Delay

If demand exceeds capacity of the work zone, it is assumed that a queue will form. If traffic volume remains constant during a given hour, then the average delay for each hour a queue is present (DQUE), in vehicle hours, is the average of the accumulated vehicles in the queue at the beginning of hour i ($ACUM_{i-1}$) and at the end of the hour i ($ACUM_i$), and is written as

$$DQUE_i = \frac{ACUM_{i-1} + ACUM_i}{2}$$ (14)

where
$ACUM_i = ACUM_{i-1} + VL_i - CAPW_i,$
$CAPW$ = restricted capacity through work zone (vph) for hour i, and
VL_i = vehicle demand during hour i.

In the first hour, there is no queue at the beginning of the hour so $ACCUM_0 = 0$. The queue at the end of the hour, $ACCUM_1 = V_1 - C_1$, so the average delay during the first hour is

$$DQUE_1 = \frac{0 + (V_1 - C_1)}{2} = \frac{V_1 - C_1}{2}.$$ (15)

If the queue dissipates during hour i, then the delay calculation must be modified by the proportion of the hour that a queue was present ($PQUE_i$), and is expressed as

$$PQUE_i = \frac{V_{i-1} - C_{i-1}}{(C_i - C_{i-1}) - (V_i - V_{i-1})} = \frac{ACUM_{i-1}}{CAPW_i - VL_i}.$$ (16)

Once the average delay is calculated, then the cost of the delay ($CQUE_i$) is calculated as

$$CQUE_i = (DQUE_i)(CUF)(PTC \bullet VLT_t).$$ (17)

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The average length of queue (QUEL$_i$), in kilometers, can also be estimated, assuming an average distance of 12 meters for each vehicle as

$$QUEL_i = \frac{0.012(DQUE_i)}{(TL)} \qquad (18)$$

where   TL = total number of lanes upstream of the work zone

For the hour when the queue dissipates,

$$QUEL_i = \frac{0.012(DQUE_i)}{(TL) \bullet PQUE_i}. \qquad (19)$$

Cost of Speed-Change Cycles

An additional delay cost is the slowing down and returning to the approach speed, as a result of the presence of a work zone (CDSC). Work zone data indicates a relationship between the distance traveled, in kilometers, during the speed-change cycle (DSC) to be a function of the V/C ratio through the work zone, written as

$$DSC = 0.8045 + 0.402(\frac{V}{C_{wz}}), \qquad (20)$$

with the constraint that DSC $\leq$ 1.21.

If the speed is reduced and increased at an approximately constant rate, then the delay cost can be calculated as

$$CDSC = (DSC)(\frac{2}{SP_{ap} + SP_{mn}} - \frac{1}{SP_{ap}})(VL)(CUF)(PTC \bullet VLT_c + \frac{PTT \bullet VLT_t}{0.9}). \qquad (21)$$

There is a change in vehicle operating costs resulting from speed change cycles. The speed-change costs per 1000 vehicle kilometers for cars (SPCC) and trucks (SPCT) are calculated as

$$SPCC = -3.2434 + 0.6986(SP_{ap}) - 0.6914(SP_{mn}), \text{ and} \qquad (22)$$

$$SPCT = -20.067 + 4.427(.9SP_{ap}) - 4.154(.9SP_{mn}). \qquad (23)$$

The additional operating cost of the speed-change cycle (CSPC) is

$$CSPC = (\frac{VL}{1000})(CUF)(PTC \bullet SPCC + PTT \bullet SPCT). \qquad (24)$$

If a queue is present, then additional speed-change operating costs (CSPQ) must be added. These costs are written as

$$CSPQ = (\frac{VL}{1000})(CUF)(3 \bullet QUEL)(3.743 \bullet PTC + 19.773 \bullet PTT). \qquad (25)$$

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During the hour the queue dissipates, the above equation for CSPQ is multiplied by the percentage of the hour that the queue is present (PQUE).

Change in Vehicle Running Costs

The change in car running costs (VOC_c) and truck running costs (VOC_t) per 1000 vehicle kilometers can be calculated by the following equations:

$$VOC_c = f(SP_{wz}) - f(SP_{ap}), \text{ and} \tag{26}$$

$$VOC_t = g(.9SP_{wz}) - g(.9SP_{ap}) \tag{27}$$

where
$$f(SP) = (395.6898)e^{.00955(SP)}(0.6215*SP)^{-.45525}, \text{ and}$$
$$g(SP) = (179.1466)e^{.013799(SP)}(0.6215*SP)^{-.35902}$$
$$+(1201.8847)e^{.0200123(SP)}(0.6215*SP)^{-.79202}.$$

The change in vehicle running costs (OC) is then calculated as

$$OC = (\frac{VL}{1000})(CUF)(CLL)(VOC_c \bullet PTC + VOC_t \bullet PTT). \tag{28}$$

If a queue forms, the average speed through the queue (SP_q) can be calculated as

$$SP_q = (\frac{SP_1}{2})[1 + (1 - \frac{C_{wz}}{C_{ap}})^{\frac{1}{2}}] \tag{29}$$

where
C_{ap} = normal capacity (vph).

When a queue is present the the change in operating costs for cars ($QVOC_c$), the change in operating costs for trucks ($QVOC_t$), and the total change in vehicle operating costs due to the queue are calculated as

$$QVOC_c = f(SP_q) - f(SP_{ap}), \tag{30}$$

$$QVOC_t = g(.9SP_q) - g(.9SP_{ap}), \text{ and} \tag{31}$$

$$QCQ = (\frac{VL}{1000})(CUF)(QUEL)(QVOC_c \bullet PTC + QVOC_t \bullet PTT). \tag{32}$$

During the hour the queue dissipates, OCQ is multiplied by PQUE.

Total User Costs

Total hourly user costs (THC) are the sum of the component user costs and are written as

$$THC = CQUE + CDWZ + CDSC + CSPC + CSPQ + OC + OCQ. \tag{33}$$

The hourly costs are summed up to yield the daily user costs resulting from restricted capacity through the work zone.

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Annual User Costs Calculations

The annual user costs for the manual method is simply the operating days per year (ODY) times the daily operating cost. The annual user costs for the robotic method may be less than those of the manual method if the robotic method provides an increase in productivity over the manual method. The annual user costs for the robotic method (AUCR) is

$$AUCR = (1 - \frac{EF}{100}) \bullet ODY \bullet DUC \qquad (34)$$

where

DUC = Daily User Costs.

Final Evaluation

Data from each submodel is used to generate the following results:

1. Annual Direct Maintenance Cost Savings I&II,
2. Annual User Cost Savings I&II,
3. Annual Life Savings,
4. Direct Break Even Value, and
5. Total Break Even Value (to contractor & highway user).

Using the cost model, an economic comparison of manual maintenance methods to robotic maintenance methods can be easily accomplished. Analysis of a particular maintenance task requires the appropriate model input parameters corresponding to manual and automated operations, respectively. The results show which method is more cost effective in terms of overall costs which may include user costs. User costs are expected to be the primary concern with regard to AHS maintenance. However, these results will be useful in design of equipment since one can explore the economic tradeoffs of completely automated systems to systems that have a higher degree of human interfacing.

Return on Investment Evaluation

Changes in the value of money, interest payable, and the rate of return on the money invested all provide factors that can be evaluated and considered in deciding if investment in a robot or automation project is worthwhile. If the overall time scales under consideration are short, changes in money values owing to inflation or interest rates are then generally ignored. The investor should decide what is the minimum rate of interest or other return that would be required for the project. This is called the minimum attractive rate of return (MARR). For very short time periods the formula

$$MARR = S \bullet \frac{100}{I} \qquad (35)$$

gives the MARR percentage where S = the annual savings resulting from the robot and I = the initial investment (Dorf, 1988).[3]

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Time Value of Money

When the working life of the investment is expected to be more than a couple of years it is useful to consider the time value of money method. Since robots are usually application flexible and reliable, they can have a working life of at least 8 years in many cases (Dorf, 1988).[3] The concept of net present value gives the current value of the robot if the gains in future years are converted to the amount of money that if invested at the required rate of return, would give the same amount of cash at the future date (Dorf, 1988).[3] The value of the required investment for each year is found by

$$P = S\left(\frac{1}{(1+MARR)^n}\right) \tag{36}$$

where

P = present value of a future amount,
S = annual savings resulting from the robot, and
n = years at interest rate.

The total present value of all the gains to be made from the project over the next n years is

$$P_T = \sum_{n=1}^{L} S\left(\frac{1}{(1+MARR)^n}\right) \tag{37}$$

where

L = the working life of the robot in years.

To determine if the project will be profitable, the estimated cost of the robot should be subtracted from P_T. This value is the net present value of the robot. Within the Demos model P_T is referred to as the break even value of the robot since if the initial cost of the robot was equal to P_T then the net gain or benefit of the robot would be zero.

Use of the Model

When the model is opened, Demos displays the top level of the model in an influence diagram window. An influence diagram is a graphical representation of a model, showing how different variables in the model interact. Each variable is represented by a node. A node is a box (rectangular, oval or any other shape) that represents a variable in an influence diagram. A typical influence diagram consists of a number of nodes connected by arrows. Every variable or other object in Demos has an associated object window containing detailed information. The object window contains the variable's identifier, units, class, title, description, definition, and the inputs and outputs necessary to calculate the value of the variable. The object window can be viewed by double clicking on a node. Submodels are represented by oval nodes with thick outlines. Inside each submodel is a model containing its own variables arranged as an influence diagram. Demos can perform dynamic simulation for time varying parameters. The queue accumulation **ACUM**, for example, is a dynamic variable. To use the Dynamic function you must provide a definition for the system variable **TIME**. In this case **TIME** is simply a list of the hours of the day 0 through 23. Each dynamic variable is indexed to **TIME**. The dynamic function calculates the value of a variable at each element of time. The input data to the model is in two formats. The parameters of the problem are entered as single numerical values. To change the value of a

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parameter, double click on the node that represents that variable. This will open the object window which shows the attributes of the object including its class, identifier, title, units, description, input and outputs. Now the cursor can be moved to the definition line and the value of the object can be changed. Traffic volume and capacity are entered as tables since a value must be specified for each hour. To edit tables, open the object window then click on the edit table bubble. The robot life is represented by the index variable **LIFE.** To increase or decrease the life of the robot simply extend or shorten the list of years that are specified in the object window. To view results open the desired object window and click on the ? bubble.

Output screens for the DEMOS model are given in the appendix. The structure of the model and information about each element has been provided.

Chapter 4
Case Studies

In this chapter two case studies are developed. The first case investigates the installation of discrete magnetic markers that are used for vehicle control. The second case investigates pavement surface repairs. In each case, a manual method is compared with an equivalent robotic method. Problem formulation and results are presented.

Magnetic Marker Case Study

This case study is presented to demonstrate how an economic analysis may be completed for a particular maintenance task. The object of the study is the installation of discrete magnetic markers that are used by some possible AHS configurations for lateral vehicle control. The magnetic markers are sometimes called magnetic nails and are completely embedded within the roadway. The details of magnetic marker installation and possible automated installation systems have been investigated by Broverman (1994).[1] This study compares manual installation of magnetic markers with an equivalent automated process. The corresponding data will then be entered into the cost model and the results will be presented.

Manual Installation of Magnetic Markers

Manual installation of magnetic markers is a three step process. The first step is to locate the desired position for the marker. This task will require a survey crew. The second step is to drill a hole in the pavement. This can be accomplished by a two man crew using a hammer drill. The third step is to locate the correctly coded marker and force it into the hole using a driving device such as a mallet. In addition to the manpower requirements for the actual installation of the magnetic marker there are some supporting tasks that are required. A driver for the support vehicle is needed. Also, a driver for a shadow truck is needed since the drilling crew would be exposed to traffic. Supporting tasks, such as lane closure and signing, are provided by a separate crew which will not be affected by the method of installation. The estimated manpower and time requirements for manual installation of magnetic markers are specified in table 3.

Table 3. Estimated requirements for manual installation of magnetic markers.

Operation	# workers required	Time/marker (min.)
Survey guide path	2	5
Drill hole	1	2
Insert marker	1	0.5
Support truck driver	1	*
Shadow truck driver	1	*
Total	6	7.5

* does not add any additional time to the installation process

Automatic Installation of Magnetic Markers

Several concepts have been developed by Broverman (1994) for the automatic installation of magnetic markers.[1] For this study, an integrated system using the Painted Line follower along with the Drill-then-Press unit will be considered. The Painted Line Follower rides along a previously painted center line. The line could be quickly painted using methods similar to conventional lane demarcation methods. Currently lines can be painted at speeds up to approximately 45 kilometers per hour. For markers spaced 4 meters apart the line painting task will take about one third of a second for each marker. Since the painting of lines is relatively inexpensive and the line follower may possibly use existing lines, the cost of painting the line will not be included in this analysis. The magnetic markers would be installed along the center of this line, with the operator locating the center of the line by eye. A linear slide may be used to adjust the exact position of the installation device. Longitudinal spacing would be determined using an encoder wheel. Once the location is determined, the Drill-then-Press Unit first drills a hole in the pavement large enough for compression fitting of the magnetic marker. It then slides to allow an air cylinder to press the marker into the hole. Because the marker is pressed into the hole, no additional sealing should be needed to hold the marker in place (Broverman, 1994).[1] An automated sorting and feeding system will transfer markers to the Drill-then-Press unit. This system will require only one operator and no shadow vehicle since no workers will be exposed to traffic. The estimated manpower and time requirements for this method are specified in table 4.

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Table 4. Estimated requirements for automated Installation of magnetic markers.

Operation	# workers required	Time/marker (min.)
Position vehicle	1	0.5
Drill hole	*	0.25
Insert marker	*	0.25
Total	1	1

* does not require any additional workers

Analysis of Magnetic Marker Installation

For this case study, the following installation scenario will be considered: Magnetic markers are to be installed 4 meters apart on the automated lane of a three lane highway. The left lane of the highway is automated with a capacity of 4000 vph. The other two lanes are conventional with a capacity of 2000 vph. The operation is to take place 7 hours a day for which one mile sections of the lane are closed at a time. There is enough work to sustain the manual operation for 250 days. Average hourly traffic volume and work zone capacity is specified. The value of time is $20.00 per hour for trucks and $10.00 per hour for cars. Traffic is eight percent trucks. The equipment operating cost of the manual method is assumed to be the same as the robot operating cost. The economic life of the robot is 5 years. The minimum attractive rate of return is 15 percent for the robot investment. Material costs are the same for the manual and robotic methods. Traffic volume and work zone capacity corresponding to a three lane highway with one AHS lane are specified in table 5.

Table 5. Hourly traffic volume and capacity data for magnetic marker installation.

Hour	Traffic Volume	Capacity
1	1000	2900
2	1200	2900
3	1300	2900
4	900	2900
5	1000	2900
6	4000	8000
7	7500	8000
8	7000	8000
9	6500	8000
10	6000	8000
11	5700	8000
12	5500	8000
13	5700	8000
14	6200	8000
15	6700	8000
16	6900	8000
17	4200	8000
18	3200	8000
19	2300	8000
20	1500	8000
21	1200	8000
22	1100	8000
23	1000	2900
24	1000	2900

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Input data to the cost model for this scenario is outlined below:

WZD = 1.6 kilometers
# of Lanes Upstream = 3
VLT_c = $10.00/hr
VLT_t = $20.00/hr
PTT = 8%
CUF = 1.0
NOFW = 4
HPD = 24 hrs
ODY = 250 days
WAGE = $25/hr
NOFWR = 1
WAGER = $25/hr
ROC = $0/hr
EF = 87%
LIFE = 4 years
MARR = 15%

Upon entering the above data, the cost model yields the following results: The annual operating cost savings of using the automated method of magnetic marker installation is $194,000 which is due to the decrease in the number of workers required and the increase in efficiency of the operation. The annual user cost savings is $49,000, which is most sensitive to the time and duration of the shutdown and the efficiency of the operation. The direct break even value of the robot is $552,000 and the total break even value of the robot including user and direct cost savings is $692,000. In this case it was found that the value of the robot is mostly a result of the direct cost savings. The value added to the robot from user cost savings is small since work was performed only during off peak hours having very litttle effect on traffic flow.

Case Study of Automated Pavement Surface Repairs

This case study is based on research which was supported by the Strategic Highway Research Program (SHRP) and the California Department of Transportion (Caltrans). Automated crack sealing has been investigated and a prototype Automated Crack Sealing Machine (ACSM) was built and tested. It was found that the crack sealing crew size could be reduced from eight workers to four workers. In addition to the reduction in crew size the ACSM can provide a 30 percent increase in time efficiency. An increase in quality of repairs may also be achieved, which may reduce the frequency that crack sealing operations are needed (Velinsky, 1993).[12] In addition to comparing manual crack sealing to automated crack sealing, this study will compare crack sealing operations on an automated highway to crack sealing operations on a conventional highway.

Manual Sealing of Cracks in Highway Pavement

The first step in the preparation of the crack calls for the removal of loose materials from the crack and the creation of a reservoir to accept the sealant. Routers are commonly used to

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perform this function. The crack reservoir must then be cleaned and dried before application of the sealant. This may be accomplished with a sandblaster or hot-air lance. The next step involves dispensing sealant from a wand which is attached to a vehicle carrying a sealant melter. Crack sealing is a tedious, labor-intensive operation. The approximate cost of crack sealing is $1100 per kilometer of which 66 percent is attributed to labor (Velinsky, 1993).[12] On average, the whole operation requires eight workers. Supporting tasks, such as lane closure and signing are provided by a separate crew.

Automated Sealing of Cracks in Highway Pavement

A complete description of the operation of the ACSM can be found in (Velinsky, 1993).[12] For the purpose of this study a brief description will be given. The ACSM is comprised of two independent primary machine systems which address longitudinal and general cracks, respectively. Vision sensing systems are used to locate pavement crack positions. The general crack sealing machine uses a robot positioning system that receives data from the vision system to guide the sealant applicator along the crack. The longitudinal crack sealing machine uses a robotic positioning system with feedback control from a laser range finder based sensor to guide the sealant applicator along longitudinal cracks only. The whole operation requires 4 workers. Again, supporting tasks such as lane closure and signing are provided by a separate crew.

Analysis of Robotic Crack Sealing

For this case study, the following crack sealing scenario will be considered: All parameters are identical for manual highway case and the AHS case except that the traffic volume and capacity have been adjusted to correspond to the two different highway scenarios. The crack sealing operation is to take place in the left lane of a 3 lane highway. For the AHS case, the left lane of the highway is automated with a capacity of 4000 vph. The other two lanes are conventional with a capacity of 2000 vph. For the conventional highway case, each lane is assumed to have a normal capacity of 2000 vph. During a lane shutdown the remaining two lanes have a combined capacity of 2900 vph for both cases. The operation is to take place 13 hours a day for which one mile sections of the lane are closed at a time. There is enough work to sustain the manual operation for 250 days. Average hourly traffic volume and work zone capacity is specified. The value of time is $20.00 per hour for trucks and $10.00 per hour for cars. Traffic is 8% trucks. The equipment operating cost of the manual method is assumed to be the same as the robot operating cost. The economic life of the robot is 10 years. The minimum attractive rate of return is 15 percent for the robot investment. Material costs are the same for the manual and robotic methods. Traffic volume on the manual highway is assumed to be 25 percent less than the the volume of the automated highway. Traffic volume and work zone capacity corresponding to both highway scenarios are specified in table 6.

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Table 6. Volume and capacity for the crack sealing study.

Hour	Manual Highway		Automated Highway	
	Volume	Capacity	Volume	Capacity
1	750	2900	1000	2900
2	900	2900	1200	2900
3	975	2900	1300	2900
4	675	2900	900	2900
5	750	2900	1000	2900
6	3000	6000	4000	8000
7	5630	6000	7500	8000
8	5300	6000	7000	8000
9	4875	6000	6500	8000
10	4500	6000	6000	8000
11	4280	6000	5700	8000
12	4130	6000	5500	8000
13	4280	6000	5700	8000
14	4650	6000	6200	8000
15	5030	6000	6700	8000
16	5180	6000	6900	8000
17	3150	2900	4200	2900
18	2400	2900	3200	2900
19	1730	2900	2300	2900
20	1130	2900	1500	2900
21	900	2900	1200	2900
22	830	2900	1100	2900
23	750	2900	1000	2900
24	750	2900	1000	2900

Input data to the cost model for both cases is outlined below:

WZD = 1.6 kilometers
# of Lanes Upstream = 3
VLT_c = $10.00/hr
VLT_t = $20.00/hr
PTT = 8%
CUF = 1.0
NOFW = 8
HPD = 16 hrs
ODY = 250 days
WAGE = $25/hr
NOFWR = 1
WAGER = $25/hr
EF = 30%
LIFE = 10 years
MARR = 15%

Results for the Crack Sealing Study are based on the cost savings of using the automated crack sealer compared to conventional crack sealing methods and are listed below in table 7.

Table 7. Results for the crack sealing study.

	Automated Highway	Manual Highway
Annual Operating Cost Savings	$520,000	$520,000
Direct Break Even Value	$2,600,000	$2,600,000
Annual User Cost Savings	$2,900,000	$47,000
Combined Annual Cost Savings	$3,400,000	$567,000
Combined Break Even Value	$17,100,000	$2,850,000

The above results indicate a large difference in user cost savings between the automated and conventional highways. The difference here is a direct result of the 25 percent greater traffic volume that was predicted for the automated highway case. Increasing the efficiency of maintenance operations and minimizing the impact of maintenance operations on traffic flow is therefore more important for an automated highway than for a manual highway. These results confirm that the benefits of automated maintenance and construction will increase as the traffic volume on highways is increased through automation.

Chapter 5
Conclusions and Recommendations

Conclusions

The purpose of this study was to investigate the costs and benefits of robotic construction and maintenance of automated highway systems. The cost of congestion on major highways has become very high indicating the need for increased highway capacity and resulting in the conceptual development of automated highway systems. As existing highway systems deteriorate, labor costs have increased, resulting in the need and development of more efficient and safer highway maintenance techniques using automation and robotics. Robotic highway maintenance has the potential to decrease the costs of highway congestion, labor, and worker accidents by speeding up highway maintenance operations, decreasing the number of workers required, and exposing fewer workers to the danger of the roadway. Although there has been economic studies of automated highway maintenance, a detailed literature search indicates that an economic study of robotic construction and maintenance of automated highway systems has not been presented.

To begin the development, in Chapter one, a general description of the problem was presented, describing how an automated highway system can reduce traffic congestion and outlining the need for improved construction and maintenance techniques.

In Chapter two, the costs associated with AHS maintenance were outlined and the concept of direct and user costs is introduced. The concept of net present value was introduced as a method to quantify the benefits of a proposed automation project.

In Chapter three, the cost benefit model was presented. The model is designed to estimate user and direct costs associated with a particular maintenance or construction task. The costs are calculated for a manual method and a proposed robotic method. If the robotic method provides an overall cost savings, then the value of the robot is calculated using the time value of money method. Calculations used by the model were described in detail and user instructions were given.

In Chapter four, three case studies were presented. The first case study investigates the installation of discrete magnetic markers. The procedure for installation was described for both the manual and the automated case. The next two studies look at automated crack sealing and compare the cost benefits of automated crack sealing for a conventional highway and for an automated highway. The analysis of each case was performed using the DEMOS model and the results were presented.

Recommendations

As a final section of this thesis, recommendations concerning the development of the computer model and corresponding framework of the analysis will be made. Since AHS development is in an early stage the model was developed in a general fashion so as not to limit its use. The input variables were chosen based on current trends in AHS research and development. However, as development of the AHS progresses and maintenance and construction requirements become more defined, care must be taken to be sure that all the costs are accounted for.

The dollar value of the benefits of automated maintenance and construction were derived partly from the decrease in vehicle delay and additional operating costs that result from reduced traffic congestion. However, in addition to decreased vehicle delay and operating

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costs there are additional benefits to the society such as decreased air pollution and energy usage. The value of these benefits to society were not calculated in this paper but they could be very substantial. A method to quantify the life savings associated with employing a robotic method which removes maintenance workers from the dangers of the roadway was given in chapter three. The life savings accounts for the fewer number of workers who would be accidentally killed during a maintenance operation. However the savings resulting from fewer workers being injured on the job was not considered. There is also the possibility that additional savings may result from fewer highway users being injured or killed due to more efficient maintenance and construction methods. Further research should explore these additional benefits of automated maintenance and construction methods.

The user cost part of the model was developed primarily for the case of highways with more than one lane in each direction. However, the potential for automation of two lane rural highways exists. In this case the calculation of delay and user costs is different since traffic must be controlled using a single lane for both directions. Vehicle delay associated with maintenance or construction activity on two lane highways has been investigated by Cassidy, Son, and Rosowsky (1993).[2] Their work would be useful in modifying the cost model for the two lane case.

The last topic relates to the results of the case study. Although the input data are rough estimates based on current AHS research, there are some concepts that can be extracted from the results. For the case of magnetic marker installation, the study concludes that user cost savings constitute the largest part of the benefits of the robotic method. This means that the majority of the value of this automation project is to the users. The development of robotic equipment for the maintenance and construction of automated highway systems is therefore, more important to the driving public than to road maintenance contractors. A robotic method that may be only marginally profitable to the contractor may prove very beneficial to users. Traffic agencies must consider this concept when they accept the lowest bid for construction and maintenance work. Depending on the efficiency of the contractors operation, the lowest bid may or may not be the most economic for the state as a whole. This issue will become increasingly important as traffic volume increases and the performance of our highways is increased through automation. In fact, it may become reasonable to award contracts based on both user costs and direct costs. That is, the procedures of the contractor as it relates to lane closures, time of day when work will be performed, time span of work, etc. may be more important than the direct cost of the work. This would additionally validate the practice of providing cost incentives to contractors to finish projects at an expedited pace and/or cost penalties for time delays in project completion.

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APPENDIX

Demos Model Screens

This Appendix documents the details of the cost benefit model. The model is displayed using the actual printed DEMOS outputs for the entire model. First the graphical diagrams for the model are displayed showing the model structure. Following the diagrams, information related to each element or object of the model is given, except for those objects that are simple input data. The information includes the title, description, functional definition, and the inputs and outputs for each object. The information in this appendix is the equivalent of a program listing which would be given for a language such as FORTRAN.
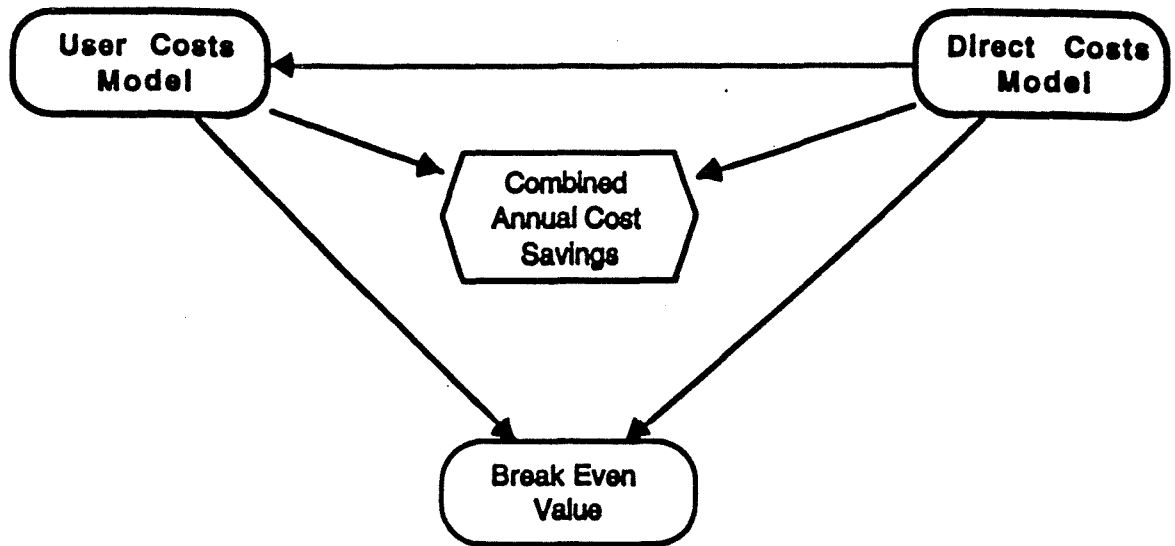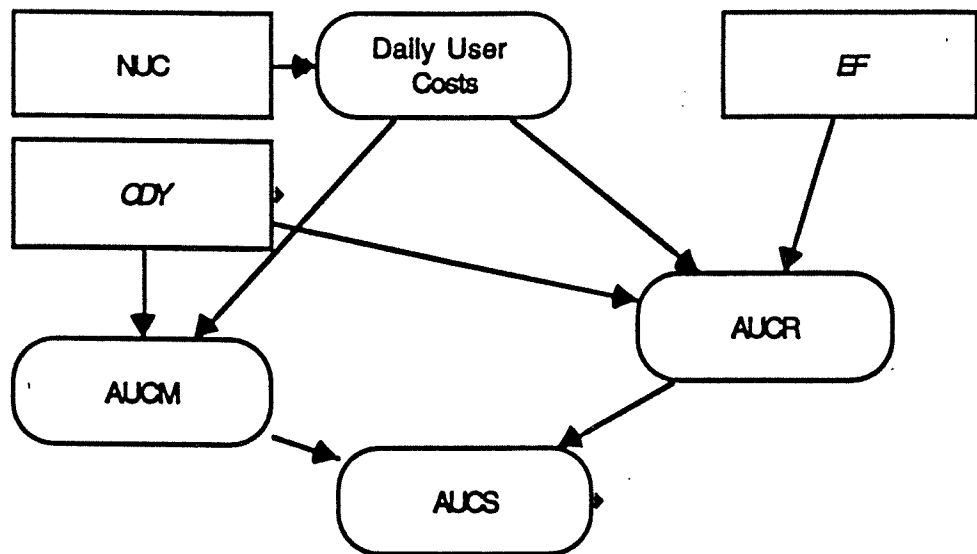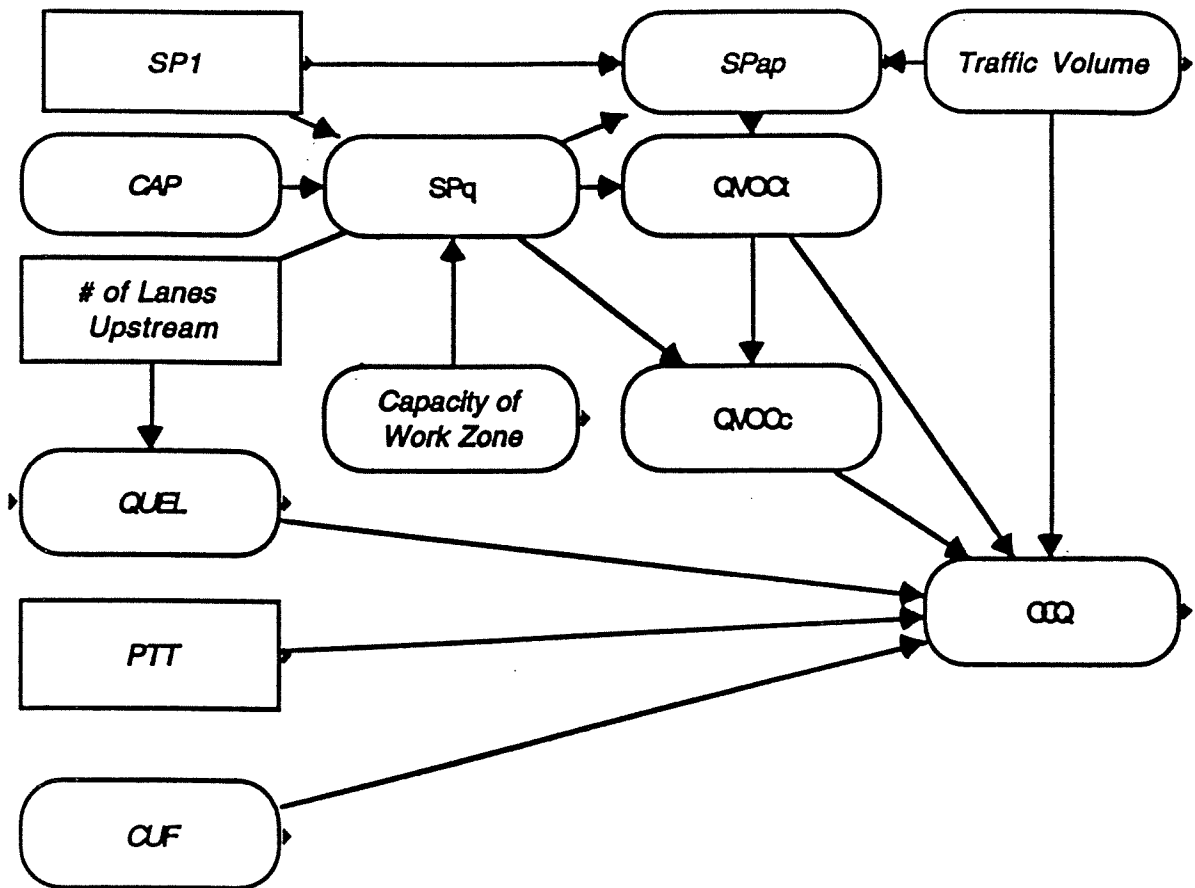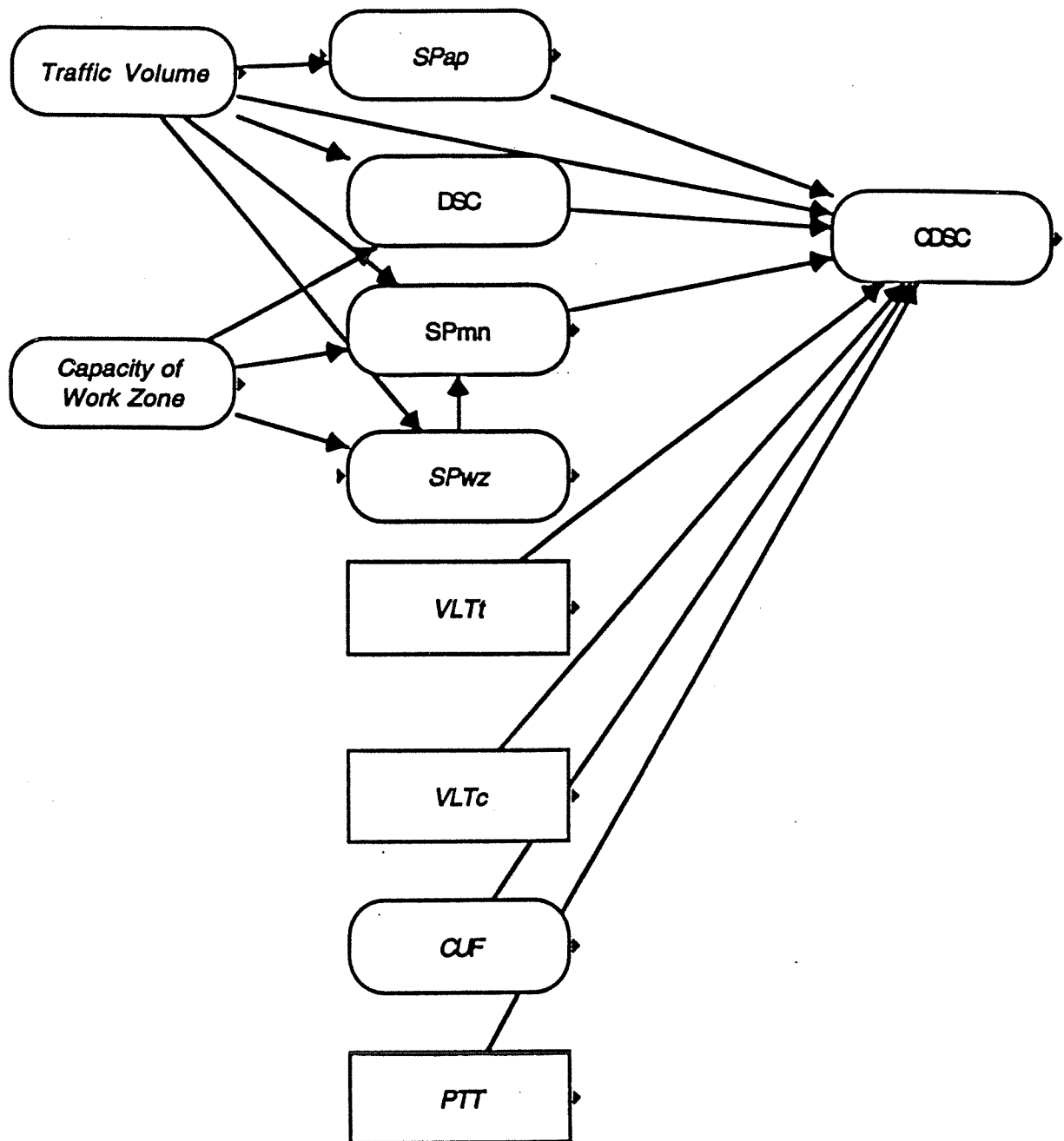
32

# of Lanes Upstream

CUF

Traffic Volume

DQUE

QUEL

CSPQ

PTT
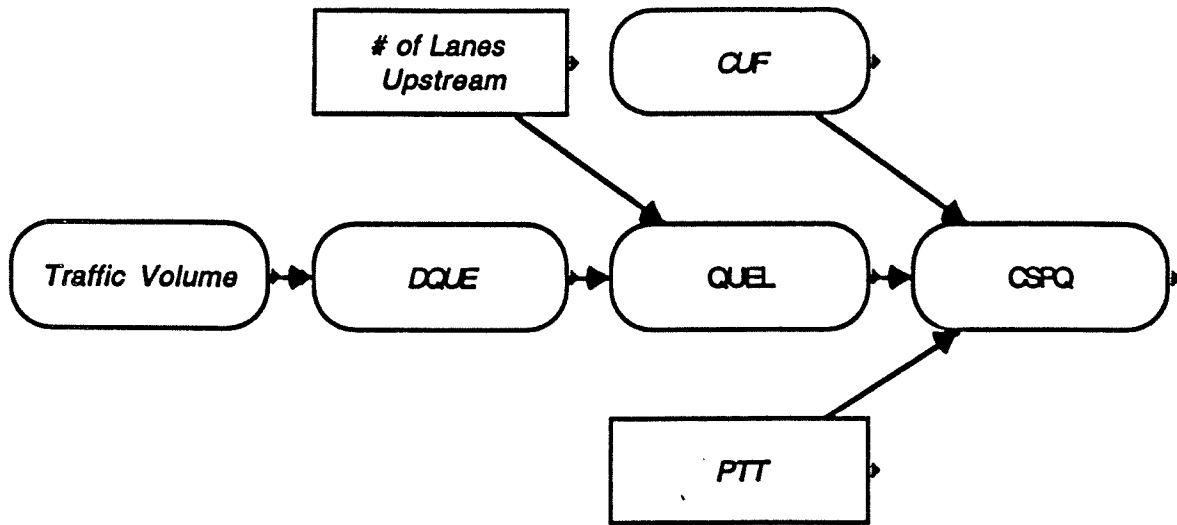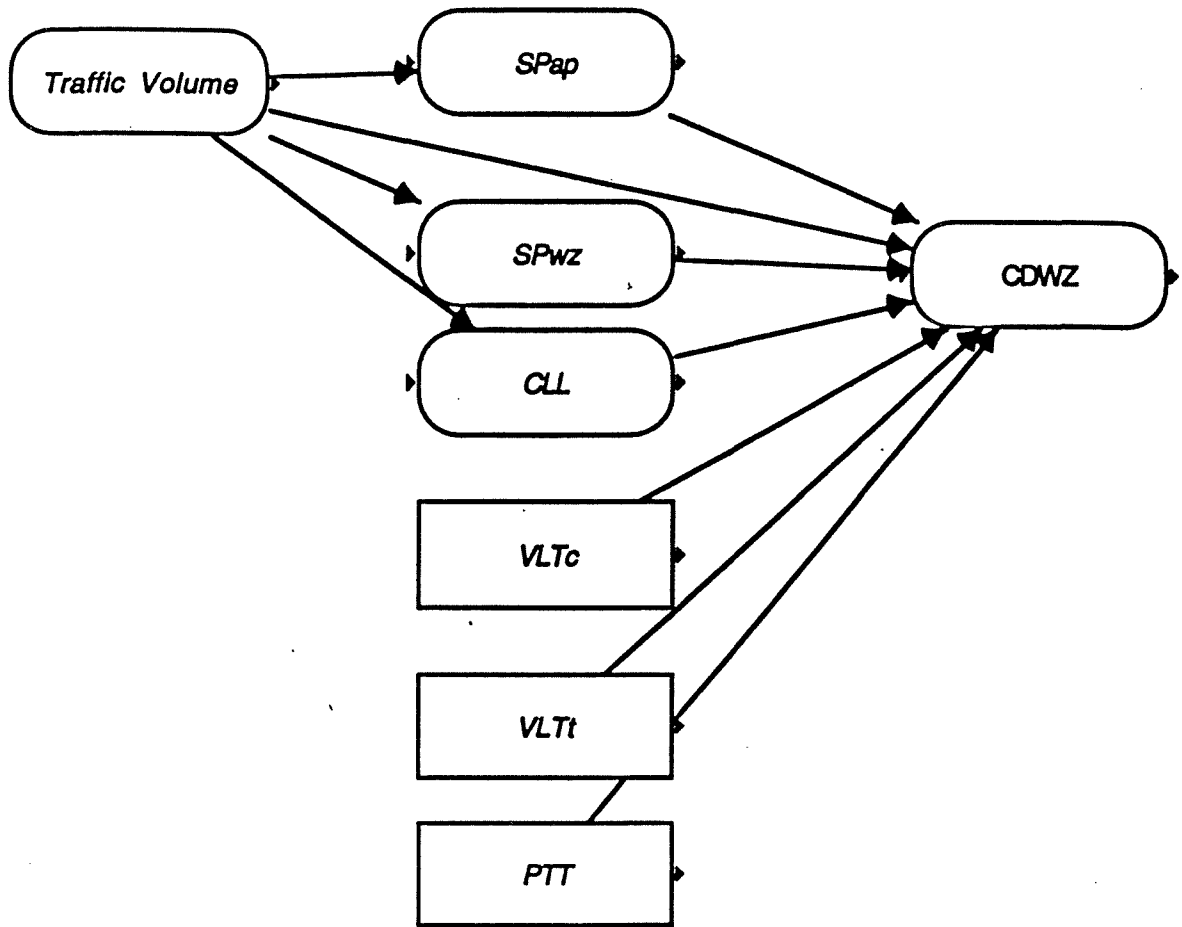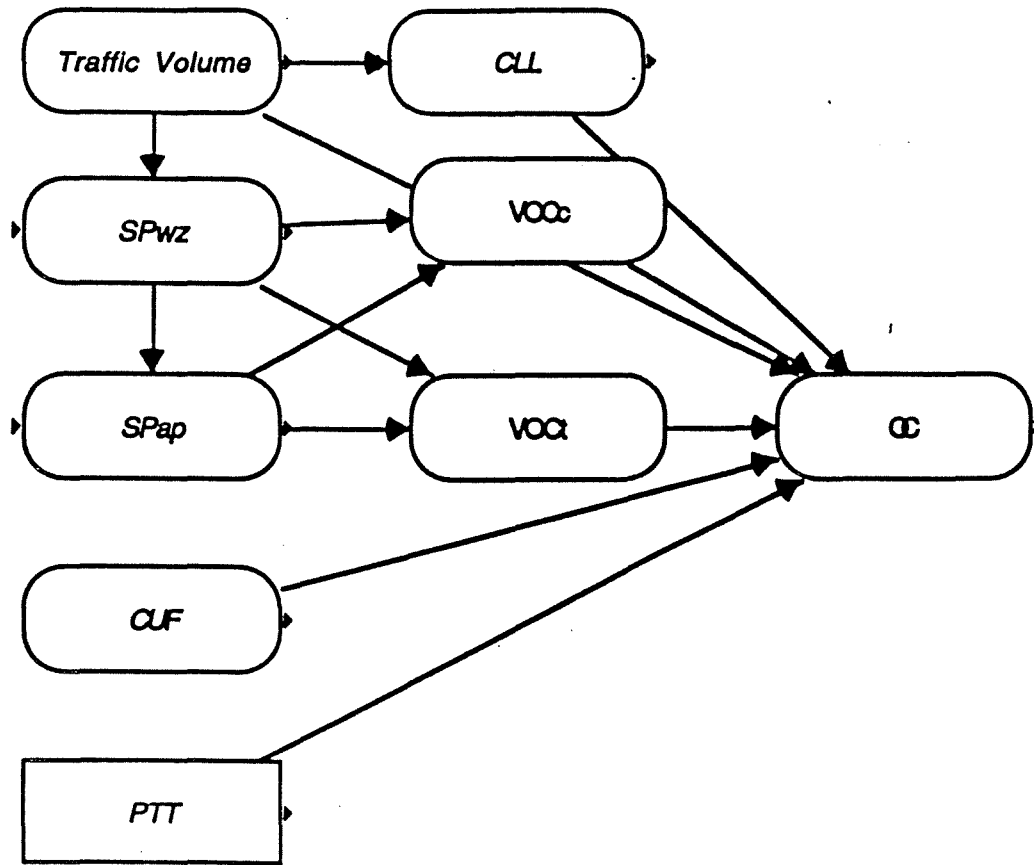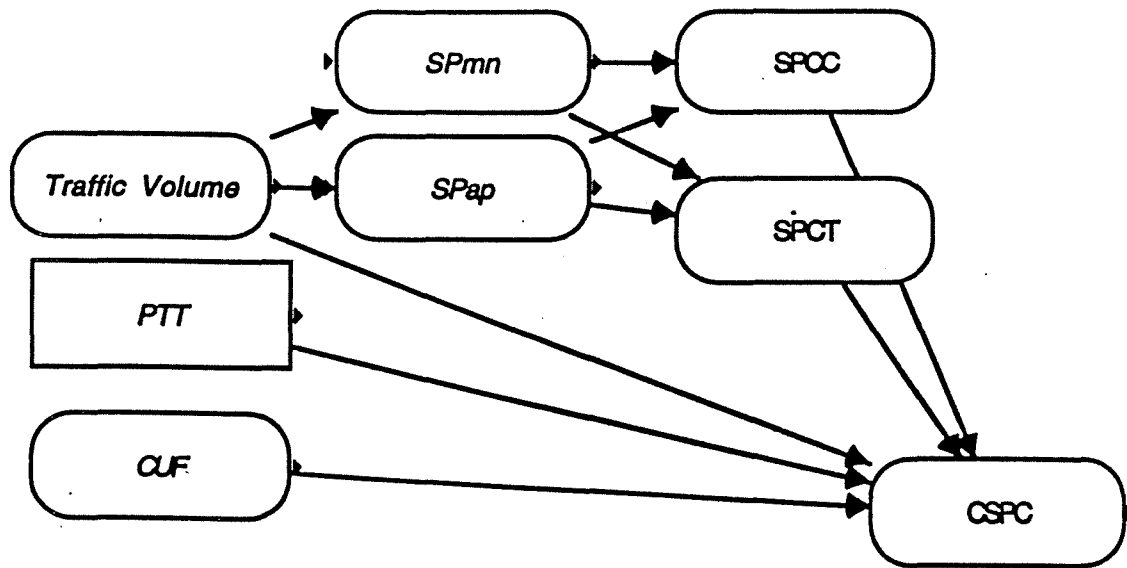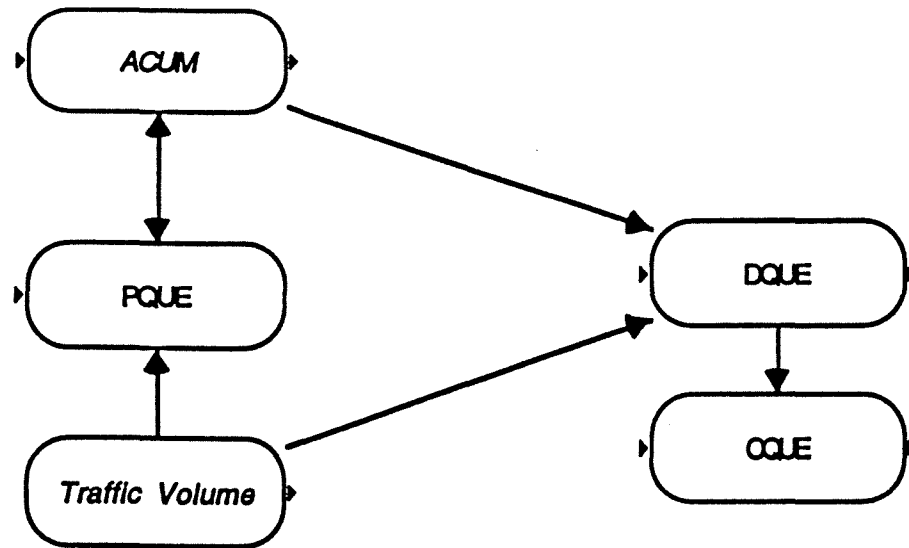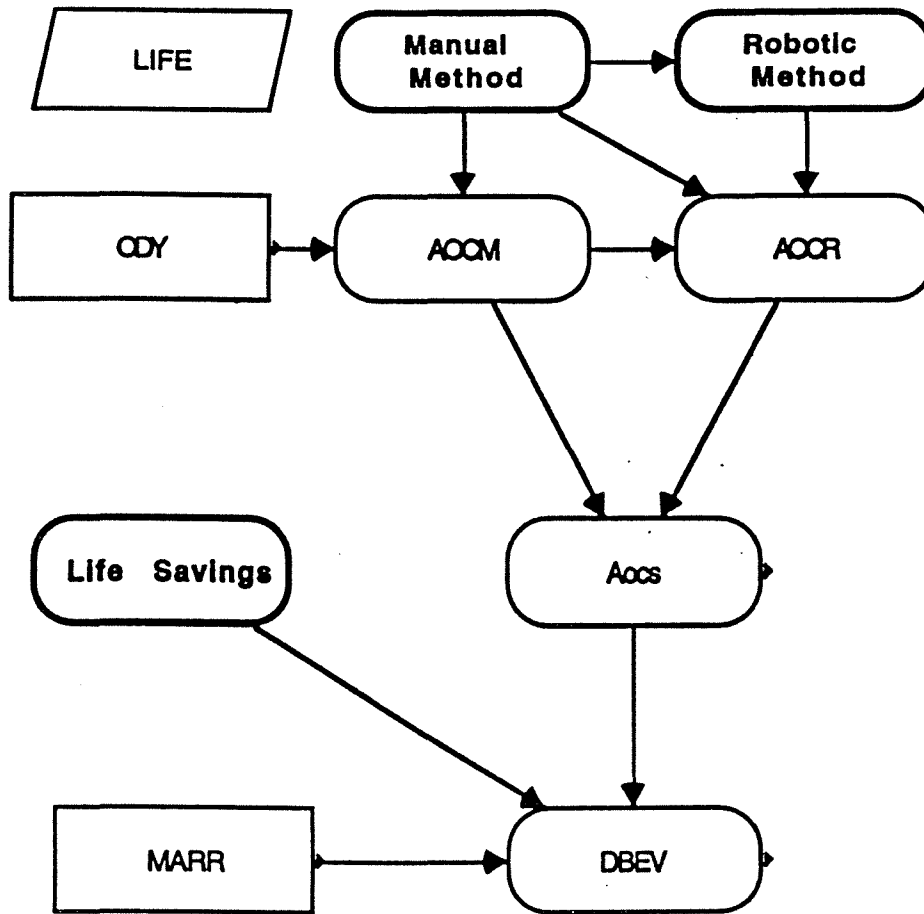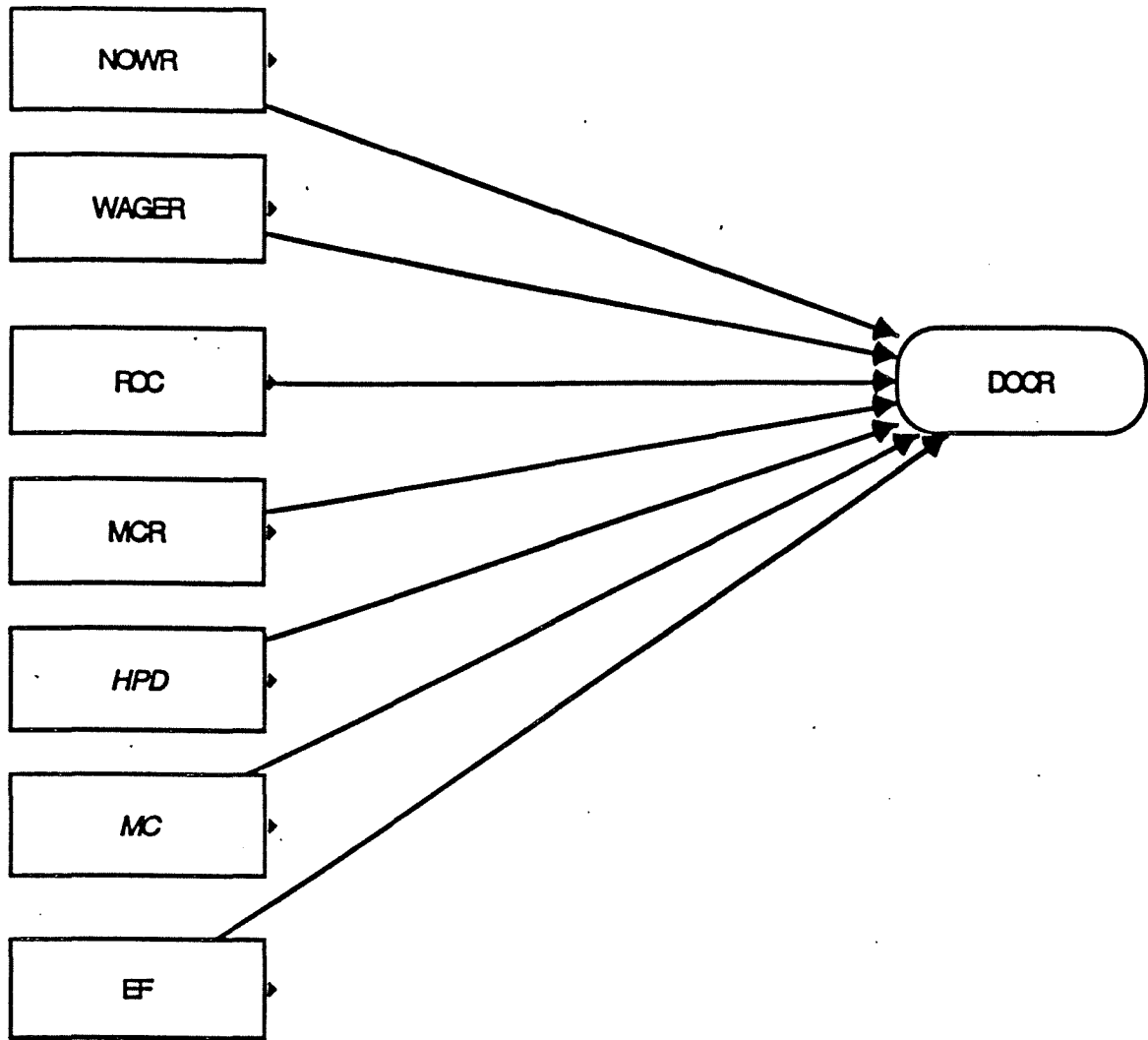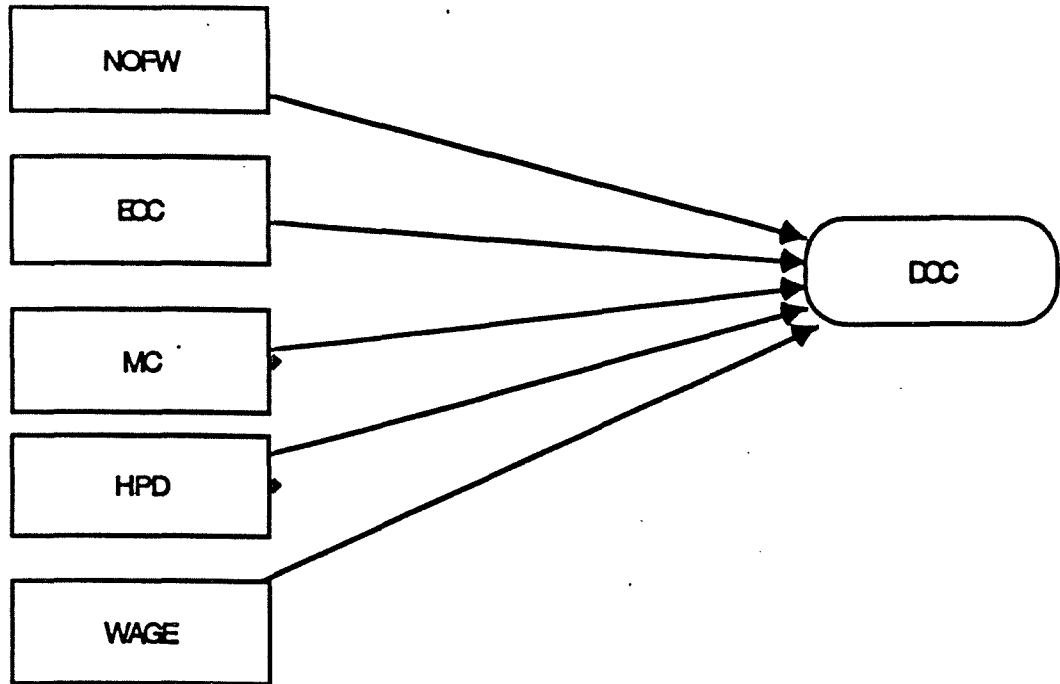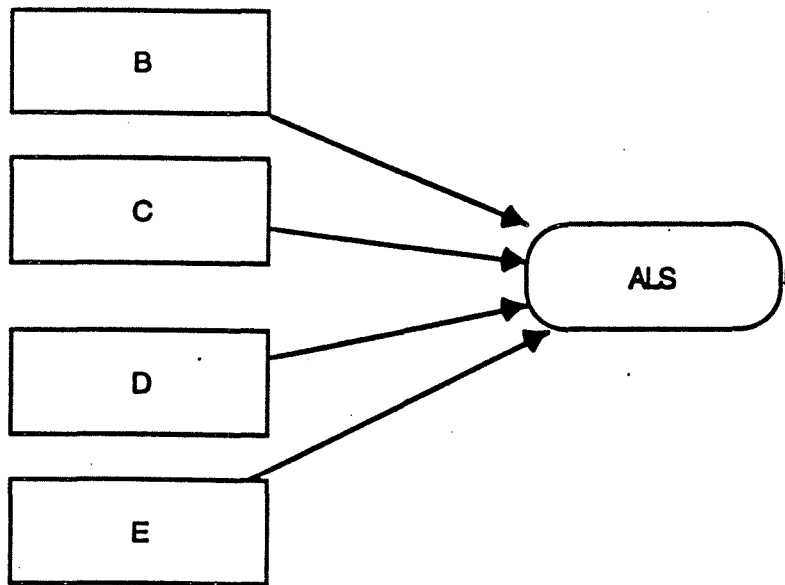
◯ Chance ▼ Acum   **Units:** #VEHICLES

     Title: ACUM

Description: ACCUMULATED VEHICLES FROM PAST HOUR

                    expr ▼
Definition: Dynamic(0,(IF ((Traffic_vo> Capacity_o) OR
                (Acum[Time-1]>(Traffic_vo-Capacity_o) AND 0)) THEN
                (Acum[Time-1]+Traffic_vo-Capacity_o) ELSE 0))

     Inputs: ◯ Capacity_o   Capacity of Work Zone
                 ⊛ Time   Dynamic Time
                 ◯ Traffic_vo   Traffic Volume

    Outputs: ◯ Dque1   DQUE
                 ◯ Pque1   PQUE
                 ◯ Spwz   SPwz

◯ **Chance** ▼ Als   **Units:** $/year

Title: ALS

Description: Annual life savings

           expr ▼

Definition: B*C*D*E

Inputs:
☐ B   B
☐ C   C
☐ D   D
☐ E   E

Outputs:
⬡ Combined_c   Combined Annual Cost Savings
◯ Dbev   DBEV

◯ **Chance** ▼ Aocm   **Units: $/year**

       Title: AOCM

Description: Anual operating cost for the manual method

             expr ▼

Definition: Ody*Doc

     Inputs: ◯ Doc   DOC

                ☐ Ody   ODY

   Outputs: ◯ Aocs   Aocs

◯ **Chance** ▼ Aocr   **Units:** $/Year

        Title: AOCR

Description: Annual operating cost for the robot

             expr ▼
Definition: Ody*((1-EF/100)*Hpd*(Wager*Nowr+Roc)+(1-Mcr/100)*Mc)

    Inputs: ☐ Ef   EF
               ☐ Hpd   HPD
               ☐ Mc   MC
               ☐ Mcr   MCR
               ☐ Nowr   NOWR
               ☐ Ody   ODY
               ☐ Roc   ROC
               ☐ Wager WAGER

   Outputs: ◯ Aocs   Aocs

◯ Chance ▼ Aocs   **Units:** $/year

　　　　Title: Aocs

Description: Annual operating cost savings

　　　　　　　　　expr ▼
Definition: Aocm-Aocr

　　Inputs: ◯ Aocm　　　ACCM
　　　　　　　 ◯ Aocr　　　ACCR

Outputs: ◯ Combined_c Combined Annual Cost Savings
　　　　　　　 ◯ Dbev　　　DBEV

○ Chance ▼ Aucm   Units: $/year

Title: AUCM

Description: Annual user costs for manual method

expr ▼
Definition: Ody*Daily_user

Inputs: ○ Daily_user   Daily User Costs
        ☐ Ody   ODY

Outputs: ○ Aucs   AUCS

◯ Chance ▼ Aucr   Units: $/year

        Title: AUCR

Description: Annual user cost for robotic method

           expr ▼

Definition: Ody*(1-Ef/100)*Daily_user

      Inputs: ◯ Daily_user Daily User Costs
              ☐ Ef   EF
              ☐ Ody   ODY

    Outputs: ◯ Aucs   AUCS

◯ Chance ▼ Aucs   Units: $/Year

  Title: AUCS

Description:

         expr ▼
Definition: Aucm-Aucr

    Inputs: ◯ Aucm   AUCM
            ◯ Aucr   AUCR

  Outputs: ◯ Bev   Break Even Value
           ◌ Combined_c Combined Annual Cost Savings

◯ **Chance** ▼ Bev   **Units: $**

      Title: Break Even Value

Description: Beak even value of robot

          expr ▼

Definition: Dbev+Sum(For I:= Life Do (Aucs/((1+(Marr/100))^I)),Life)

Inputs: ◯ Aucs   AUCS
          ◯ Dbev   DBEV
          ▱ Life   LIFE
          ▢ Marr   MARR

◯ Chance ▼ Cdwz   Units: $/hr

       Title: CDWZ

Description: Delay costs of going through the work zone at reduced speed

                expr ▼

Definition: Cll*((1/Spwz)-(1/Spap))*Traffic_vo*Cuf*(((100-Ptt)/100)*Vltc
              +Ptt*Vltt/.9/100)

Inputs: ◯ Cll   CLL
       ◯ Cuf   CUF
       ▢ Ptt   PTT
       ◯ Spap   SPap
       ◯ Spwz   SPwz
       ◯ Traffic_vo   Traffic Volume
       ▢ Vltc   VLTc
       ▢ Vltt   VLTt

Outputs: ◯ Huc   Hourly User Costs

◯ Chance ▼ CII   Units: km

Title: CLL

Description: effective length of closure

expr ▼

Definition: .16+(Wzd+.16)*(Traffic_vo/Capacity_o)

Value: **Show Result** indexed by Dynamic Time

Inputs: ◯ Capacity_o   Capacity of Work Zone   (vph) = Show Result
        ◯ Traffic_vo   Traffic Volume   (vph) = Show Result
        ▢ Wzd   WZD   (miles) = 1

Outputs: ◯ Cdwz   CDWZ
         ◯ Cc   CC

◯ **Objective** ▼ Combined_c   **Units:** $/year

       Title: Combined Annual Cost Savings

Description:

            expr ▼

Definition: Aocs+Als+Aucs

    Inputs: ◯ Als   ALS
              ◯ Aocs   Aocs
              ◯ Aucs   AUCS

⬭ **Chance** ▼ Cque   **Units: $/hr**

         Title: CQUE

Description: Hourly cost due to a que delay

           expr ▼

Definition: Dque1*Cuf*((100-Ptt)*Vltc+Ptt*Vltt)/100

    Inputs: ⬭ Cuf   CUF

              ⬭ Dque1   DQUE

              ☐ Ptt   PTT

              ☐ Vltc   VLTc

              ☐ Vltt   VLTt

   Outputs: ⬭ Huc   Hourly User Costs

◯ **Chance** ▼ Cspc   **Units: $/hr**

         Title: CSPC

Description: Additional operating cost of the speed change cycle

             expr ▼

Definition: (Traffic_vo/1000)*Cuf*(((100- Ptt)/100)* Spcc+Ptt* Spct /100)

        Inputs: ◯ Cuf   CUF
                   ☐ Ptt   PTT
                   ◯ Spcc   SPCC
                   ◯ Spct   SPCT
                   ◯ Traffic_vo Traffic Volume

      Outputs: ◯ Huc   Hourly User Costs

◯ **Chance** ▼ Daily_user   **Units:** $/day

      Title: Daily User Costs

Description: Daily user costs

          expr ▼

Definition: Sum(Huc,time)-Nuc

    Inputs: ◯ Huc   Hourly User Costs
            ▢ Nuc   NUC
            (SYS) Time   Dynamic Time

  Outputs: ◯ Aucm   AUCM
            ◯ Aucr   AUCR

◯ Chance ▼ Dbev   Units: $

　　　　Title: DBEV

Description: Break even value in terms of annual operating cost savings and life
             savings

             expr ▼

Definition: Sum(For local1 := Life Do
            ((Als+Aocs)/((1+(Marr/100))^local1)),Life)

Inputs: ◯ Als   ALS
        ◯ Aocs   Aocs
        ⃟ Life   LIFE
        ▢ Marr   MARR

Outputs: ◯ Bev   Break Even Value

◯ Chance ▼ Doc   Units: $/year

         Title: DOC

Description: Daily operating cost

                    expr ▼
Definition: (Hpd*(Wage*Nofw+Eoc)+Mc)

      Inputs: ☐ Eoc   EOC
              ☐ Hpd   HPD
              ☐ Mc   MC
              ☐ Nofw   NOFW
              ☐ Wage   WAGE

     Outputs: ◯ Aocm   AOCM

◯ Chance ▼ Docr   **Units:** $/day

    Title: DOCR

Description: Daily operating cost for the robot

      expr ▼

Definition: Hpd*(Roc+Wager*Nowr)+(1-Mcr/100+EF/100)*Mc

   Inputs: ☐ Ef   EF
       ☐ Hpd   HPD
       ☐ Mc   MC
       ☐ Mcr   MCR
       ☐ Nowr NOWR
       ☐ Roc   ROC
       ☐ Wager WAGER

◯ Chance ▼ Dque1   **Units:** veh hrs

       Title: DQUE

Description: Average delay due to a que

              expr ▼

Definition: Dynamic(0,(If ((Traffic_vo>Capacity_o)Or(Acum>0)) Then
              ((Acum[Time-1]+Acum)/2) Else 0))

     Inputs: ◯ Acum   ACUM
              ◯ Capacity_o Capacity of Work Zone
              ⑤ Time   Dynamic Time
              ◯ Traffic_vo Traffic Volume

    Outputs: ◯ Cque   CQUE
              ◯ Quel   QUEL

◯ **Chance** ▼ Dsc   **Units:** km

       Title: DSC

 Description: Distance traveled during a speed change cycle

             expr ▼
 Definition: IF(.8045+.402*(Traffic_vo/Capacity_o)) <= 1.21 THEN
                 .8045+.402*(Traffic_vo/Capacity_o) ELSE 1.21

     Value: |Show Result| indexed by Dynamic Time

    Inputs: ◯ Capacity_o   Capacity of Work Zone   (vph) = Show Result
            ◯ Traffic_vo   Traffic Volume   (vph) = Show Result

  Outputs: ◯ Cdsc1   CDSC

◯ Chance ▼ Huc   Units: $/hr

       Title: Hourly User Costs

Description: User Costs Due to Maintenance

          expr ▼

Definition: Ocq*IfPos(Ocq)+Oc*IfPos(Oc)+Cspq*IfPos(Cspq)+Cspc*IfPos(Cspc)+C
dsc1*IfPos(Cdsc1)+Cque*IfPos(Cque)+Cdwz*IfPos(Cdwz)

Inputs: ◯ Cdsc1   CDSC
        ◯ Cdwz   CDWZ
        ◯ Cque   CQUE
        ◯ Cspc   CSPC
        ◯ Cspq   CSPQ
        ◯ Oc   OC
        ◯ Ocq   OCQ

Outputs: ◯ Daily_user Daily User Costs

◯ Chance　▼ Cc　　　　　　　　　　　Units: $/hr

　　　　Title: CC

Description: The change in vehicle running costs

　　　　　　　expr ▼
Definition: (Traffic_vo/1000)*　Cuf*　CII*(Vocc*((100-Ptt)/100)+Voct
　　　　　　　*Ptt/100)

　　Inputs: ◯ CII　　　　CLL
　　　　　　 ◯ Cuf　　　　CUF
　　　　　　 ☐ Ptt　　　　PTT
　　　　　　 ◯ Traffic_vo　Traffic Volume
　　　　　　 ◯ Vocc　　　 VOCc
　　　　　　 ◯ Voct　　　 VOCt

　Outputs: ◯ Huc　　　　Hourly User Costs

◯ **Chance** ▼ Ccq   **Units: $/hr**

       Title: CCQ

Description: Change in vehicle running costs for a cue

           expr ▼

Definition: (Traffic_vo/1000)*Cuf*Quel*((Qvocc*(100-Ptt)/100)+Qvoct*Ptt/100)

      Inputs: ◯ Cuf   CUF
                 ☐ Ptt   PTT
                 ◯ Quel   QUEL
                 ◯ Qvocc   QVOCc
                 ◯ Qvoct   QVOCt
                 ◯ Traffic_vo   Traffic Volume

    Outputs: ◯ Huc   Hourly User Costs

◯ Chance ▼ Pque1   Units: %

      Title: PQUE

Description: percent of the hour that the que is present

           expr ▼
Definition: (Acum/(Capacity_o-Traffic_vo))

    Inputs: ◯ Acum   ACUM
             ◯ Capacity_o Capacity of Work Zone
             ◯ Traffic_vo Traffic Volume

⬡ Chance   ▼ Quel   **Units:** km

   Title: QUEL

Description: Length of Que

                expr ▼
Definition: Dque1*.012/ A_of_lanes

   Value: [**Show Result**]   Indexed by Dynamic Time

   Inputs: ☐ A_of_lanes   # of Lanes Upstream   = 3
              ⬡ Dque1   DQUE   (veh hrs) = Show Result

   Outputs: ⬡ Cspq   CSPQ
               ⬡ Coq   COQ

◯ **Chance** ▼ Qvocc   **Units:** $/1000veh*km

        Title: QVOCc

Description: Change in running costs for car

                expr ▼
Definition: 395.6898*exp(0.00955*Spq)*(.6215*Spq)^(-.45525)-(395.6898
                *exp(0.00955*Spap)*(.6215*Spap)^(-.45525))

    Value: |Show Result| indexed by Dynamic Time

Inputs: ◯ Spap   SPap   (km/hr) = Show Result
            ◯ Spq   SPq   (km/hr) = Show Result

Outputs: ◯ Ocq   CCQ

◯ **Chance** ▼ Qvoct　　　　　　　　　**Units:** $/hr

　　　　Title: QVOCt

Description: Change in truck running costs

　　　　　　　expr ▼

Definition: 179.1466*exp(.01379*Spq*.9)*(.55935*Spq)^(-.35902)+1201.8
　　　　　847*exp(.020012*.9*Spq)*(.55935*Spq)^(-.79202)-(179.1466*
　　　　　exp(.01379*Spap*.9)*(.55935*Spap)^(-.35902)+1201.8847*exp
　　　　　(.01379*.9*Spap)*(.55935*Spap)^(-.79202))

　　　Value: [**Show Result**]　indexed by Dynamic Time

　Inputs: ◯ Spap　　　　SPap　　　　　　　　(km/hr) = Show Result
　　　　　　　◯ Spq　　　　　SPq　　　　　　　　(km/hr) = Show Result

Outputs: ◯ Ocq　　　　　OCQ

◯ Chance ▼ Spap   **Units: km/hr**

        Title: SPap

Description: approach speed

             expr ▼

Definition: IF Traffic_vo/(2000*A_of_lanes)>1 AND (Sp3*(2-Traffic_vo/(2000*A_of_lanes))<32) THEN 32 ELSE If Traffic_vo/(2000*A_of_lanes)>1 AND (Sp3*(2-Traffic_vo/(2000*A_of_lanes))>Sp3) THEN Sp3 ELSE If ((Traffic_vo/(2000*A_of_lanes))>1) THEN (Sp3*(2-(Traffic_vo/(2000*A_of_lanes)))) ELSE IF((V2/V1)>=(Traffic_vo/(2000*A_of_lanes))) THEN Sp1+(v1*(Sp2-Sp1)/V2*(Traffic_vo/(2000*A_of_lanes)))ELSE IF (V2/V1<Traffic_vo/(2000*A_of_lanes)) AND (V2/V1<=1) THEN Sp2+(Sp2-Sp3)*(1-((Traffic_vo/(2000*A_of_lanes)-V2/V1)/(1-V2/V1))^2)^.5 ELSE 0

Value: $\boxed{\textbf{Show Result}}$ indexed by Dynamic Time

Inputs: ☐ A_of_lanes # of Lanes Upstream   = 3
          ☐ Sp1   SP1   (km/hr) = 97
          ☐ Sp2   Sp2   (km/hr) = 64
          ☐ Sp3   SP3   (MPH) = 48
          ◯ Traffic_vo Traffic Volume   (vph) = Show Result
          ☐ V1   V1   (VPHPL) = 2000
          ☐ V2   V2   (VPHPL) = 1600

Outputs: ◯ Cdsc1   CDSC
           ◯ Cdwz   CDWZ
           ◯ Qvocc   QVOCc
           ◯ Qvoct   QVOCt
           ◯ Spcc   SPCC
           ◯ Spct   SPCT
           ◯ Vocc   VOCc
           ◯ Voct   VOCt

⬡ Chance ▼ Spcc   **Units:** $/1kveh*km

Title: SPCC

Description: Speed change costs per 1000 vehicle kilometers for cars

expr ▼
Definition: -5.2187+.6986*Spap-.6914*Spmn

Value: [**Show Result**] indexed by Dynamic Time

Inputs: ⬡ Spap   SPap   (km/hr) = Show Result
            ⬡ Spmn   SPmn   (km/hr) = Show Result

Outputs: ⬡ Cspc   CSPC

◯ **Chance** ▼ Spct   **U n i t s :** $/k*veh*km

          T i t l e : SPCT

D e s c r i p t i o n : Speed change cycles per 1000 vehicle kilometers

                expr ▼
D e f i n i t i o n : -32.2883+4.427*.9*Spap-4.154*.9*Spmn

          V a l u e : **Show Result**   indexed by Dynamic Time

     I n p u t s : ◯ Spap   SPap   (k m / h r) = Show Result
                    ◯ Spmn   SPmn   (k m / h r) = Show Result

   O u t p u t s : ◯ Cspc   CSPC

◯ **Chance** ▼ Spmn   **Units:** km/hr

        Title: SPmn

Description: minimum vehicle speed through work zone

        expr ▼
Definition: Spwz-3.7-41.4*(Traffic_vo/Capacity_o)^2

    Value: [**Show Result**] indexed by Dynamic Time

Inputs: ◯ Capacity_o Capacity of Work Zone   (vph) = Show Result
        ◯ Spwz   SPwz   (km/hr) = Show Result
        ◯ Traffic_vo Traffic Volume   (vph) = Show Result

Outputs: ◯ Cdsc1   CDSC
        ◯ Spcc   SPCC
        ◯ Spct   SPCT

◯ Chance ▼ Spq   Units: mph

         Title: SPq

Description: Average speed through the que

              expr ▼
Definition: (Sp1/2)·(1+(1-(Capacity_o/CAP))^.5)

     Value: [Show Result] indexed by Dynamic Time

   Inputs: ◯ Cap   CAP   (vph) = 8000
           ◯ Capacity_o   Capacity of Work Zone   (vph) = Show Result
           ☐ Sp1   SP1   (MPH) = 60

   Outputs: ◯ Qvocc   QVOCc
            ◯ Qvoct   QVOCt

◯ **Chance** ▼ Spwz   **Units: km/hr**

Title: SPwz

Description: speed through work zone

expr ▼

Definition: (If
((((Traffic_vo/Capacity_o)>1)Or(Acum>0))And((Sp3*(2-(Traffic_vo/Capacity_o)))<32)) Then 32 Else (If
((((Traffic_vo/Capacity_o)>1)Or(Acum>0))And((Sp3*(2-(Traffic_vo/Capacity_o)))>Sp3)) Then Sp3 Else (If
(((Traffic_vo/Capacity_o)>1)Or(Acum>0)) Then
(Sp3*(2-(Traffic_vo/Capacity_o))) Else (If
((V2/V1)>=(Traffic_vo/Capacity_o)) Then
(Sp1+(((V1*(Sp2-Sp1))/V2)*(Traffic_vo/Capacity_o))) Else (If
(((V2/V1)<(Traffic_vo/Capacity_o))And((V2/V1)<=1)) Then
(Sp2+((Sp2-Sp3)*((1-(((Traffic_vo/Capacity_o)-(V2/V1))/(1-(V2/V1)))^2))^0.5))) Else 0)))))

Value: [**Show Result**] indexed by Dynamic Time

Inputs:

◯ Acum	ACUM	(#VEHICLES)	= Show Result
◯ Capacity_o	Capacity of Work Zone	(vph)	= Show Result
☐ Sp1	SP1	(km/hr)	= 97
☐ Sp2	Sp2	(km/hr)	= 64
☐ Sp3	SP3	(MPH)	= 48
◯ Traffic_vo	Traffic Volume	(vph)	= Show Result
☐ V1	V1	(VPHPL)	= 2000
☐ V2	V2	(VPHPL)	= 1600

Outputs:

◯ Cdwz	CDWZ
◯ Spmn	SPmn
◯ Vocc	VOCc
◯ Voct	VOCt

◯ Chance   ▼ Vocc   **Units:** $/kveh*km

   Title: VOCc

Description: Change in car running costs per 1000 vehicles

            expr ▼
Definition: 395.6898*exp(0.00955*Spwz)*(.6215*Spwz)^(-.45525)-(395.6
            898*exp(0.00955*Spap)*(.6215*Spap)^(-.45525))

     Value: |**Show Result**| indexed by Dynamic Time

   Inputs: ◯ Spap   SPap   (km/hr) = Show Result
             ◯ Spwz   SPwz   (km/hr) = Show Result

   Outputs: ◯ Cc   CC

◯ Chance ▼ Voct   **Units:** $/kveh*km

Title: VOCt

Description: Change in truck running costs per a 1000 vehicles

expr ▼

Definition: 179.1466*exp(.01379*Spwz*.9)*(.55935*Spwz)^(-.35902)+120
1.8847*exp(.020012*.9*Spwz)*(.55935*Spwz)^(-.79202)-(179.
1466*exp(.01379*Spap*.9)*(.55935*Spap)^(-.35902)+1201.884
7*exp(.01379*.9*Spap)*(.55935*Spap)^(-.79202))

Value: ⌈Show Result⌋ indexed by Dynamic Time

Inputs: ◯ Spap   SPap   (km/hr) = Show Result
          ◯ Spwz   SPwz   (km/hr) = Show Result

Outputs: ◯ Oc   OC