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Variable Speed Limit System Cost Benefit Analysis

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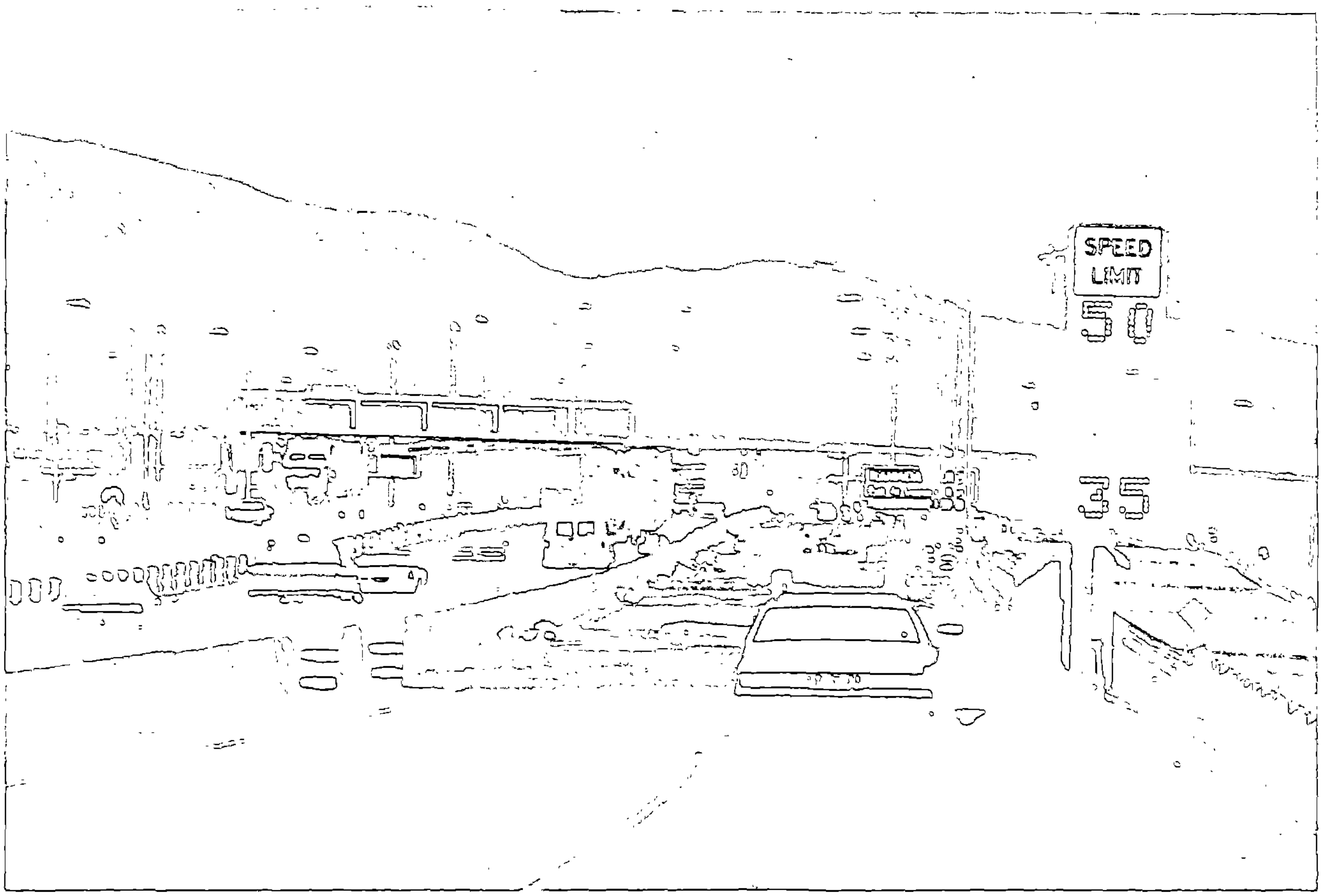

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
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FOREWORD

The Variable Speed Limit (VSL) system is to provide improved safety and efficiency in the traffic stream. The VSL is designed to show both the maximum and minimum speed boundaries based on measured, real-time traffic and environmental conditions. The system should reduce the speed differences among vehicles, thereby providing a safer traffic flow. It will provide higher speed limits for ideal conditions, thus improving efficiency. It will lower speeds when deteriorated conditions dictate a slower maximum safe speed. In addition, short messages can be displayed to warn drivers of downstream problems.

In order to evaluate the effectiveness of the VSL system, a computer model was developed. The model evaluates four scenarios: (1) Isolated--installed to operate independently, (2) Linked--in a series of stations, (3) Integrated--as a component of a larger management system, and (4) In-Vehicle--in the future as part of an "In-Vehicle" system. The model may be used to study a potential installation of the VSL by substituting site-specific data into the model for the appropriate scenario, and the model will provide the benefit/cost ratio for the proposed system. Copies of the model may be obtained from the Traffic Safety Research Division (HSR-30), 6300 Georgetown Pike, McLean, Virginia 22101-2296.

One copy of the report is being sent directly to each Regional and Division Office. A second copy will be sent to each Division Office to pass on to the State highway agency.

R. J. Betsold
Director, Office of Safety and Traffic
Operations Research and Development

NOTICE

Technical Report Documentation Page

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15. Supplementary Notes

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16. Abstract

The variable speed limit (VSL) system is designed to display both the maximum and minimum speed boundaries based on measured traffic and environmental conditions. In addition, short driver information messages can be displayed to warn of downstream conditions. The VSL can be installed to operate independently (Isolated), in a series of stations (Linked), as a component of a larger management system (Integrated), and in the future as part of an "In-Vehicle" component to provide all types of driver information (In-Vehicle).

This analysis compares the four types of VSL systems to the existing "fixed" speed limit system which can display only one speed for all conditions. The costs of the VSL equipment include its installation and maintenance, the costs of accidents include accident-induced delay costs, and time costs include time to traverse the section. A number of assumptions are made relating to projected accident rates, traverse time costs, and drivers' responses to the system.

The model, using Lotus 1-2-3, calculates the costs and benefits for the set of roadway, traffic, and weather conditions entered by the user. Four scenarios were run, one for each of the VSL types using actual site information. The benefit-cost ratios computed were 37 to 1 for the isolated system, 22 to 1 for the linked system, 55 to 1 for the integrated system, and 53 to 1 for the in-vehicle. These ratios are very sensitive to the assumptions made where actual data were not available.

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Variable speed limit, changeable speed limit, automated speed limit, benefit-costs, system costs, accident costs.	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

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SECTION ONE
INTRODUCTION

INTRODUCTION TO VARIABLE SPEED LIMIT SYSTEM AND MODEL

The Federal Highway Administration is having a "Variable Speed Limit System" designed and a prototype field tested on a section of freeway in New Mexico. The test will be minimal, however, with regard to determining motorist understanding and behavior. Because there is a need to more fully develop the potential costs and benefits associated with the variable speed limit system, this Cost Benefit Analysis and its model were developed. They will be used to determine if such a system should be implemented on a large scale, or whether the system should be limited to special circumstances.

BACKGROUND

The variable speed limit system is being designed as a speed control system to set both maximum and minimum speed boundaries on a freeway to promote the safe and efficient movement of vehicles based on traffic and environmental conditions. The system uses vehicle detectors in each lane of the roadway to measure speeds and volumes; environmental sensors to provide data on darkness and weather; changeable message signs to display speed limits and other information; and communication links between the sensors, signs, and a data processing unit. The system may be installed in four ways: (1) as an isolated location operated independently (isolated); (2) in a series of stations along a freeway with communication links connecting adjacent stations for possible interaction between stations (linked); (3) as a system component integrated into an urban freeway management system (integrated); and (4) in the future, as part of an "in-vehicle" component to give drivers direct control information which may include speed limits (in-vehicle).

Variable speed limit systems must then be compared to the existing fixed speed limit systems to determine the impact of the VSL system on motorists.

Since the number of traffic and weather condition variables and their combinations are high, a cost benefit model is needed assist the analysis.

This report documents a variable speed limit (VSL) cost benefit model and explains its uses and limitations. The model compares fixed limit highway attributes with VSL highway attributes and includes the costs of the VSL equipment and its installation and maintenance; the cost of accidents including accident-induced delay costs; and traverse time costs. The model will accept either actual (historic) data on a highway segment or projected accident rates based on assumptions. The use of projected data is necessary until sufficient historical data is gathered on newly-installed VSL systems. Any conclusions reached using the model with projected data are limited by the degree to which the projections reflect the real world.

MODEL USE AND LIMITATIONS

The model was designed to be sensitive to weather and traffic conditions because it may be used to locate highways in the nation that would most benefit from a variable speed limit system. The costs and benefits for all four of the alternative configurations are calculated for a user-defined set of weather and traffic conditions. For example if a VSL system were to be installed on Interstate 70 near Frederick, Maryland, the model user would enter the weather and traffic conditions for that section of highway into the various tables within the model. The results of the model would then show the costs and benefits associated with the installation on that section of highway.

If the user then wanted to compare the costs and benefits of a VSL system on I-70 with the costs and benefits of a VSL on Interstate 40 in New Mexico, the weather and traffic conditions for the New Mexico highway would have to be entered. The results of each of the four types of VSL configurations in the two locations would have to be compared to determine which type of configuration in which location had the most benefit.

The model calculates the costs and benefits for the set of traffic and weather conditions entered by the user. It produces benefits for each different VSL configuration under the conditions entered. It will not simultaneously compare costs and benefits for different highway conditions. The user must record the results in a saved spreadsheet (Lotus 1-2-3 /F, S) for one set of conditions and then enter the new conditions data and command the computer to recalculate the costs and benefits under the second set of conditions (Lotus 1-2-3 F9).

The model can be used in two different modes:

- o Using accident data (involvement rates) inserted by the user into the involvement rate table, or

- o Projecting accident rates (involvement rates) based on user input of the traffic characteristics (mean speed and standard deviation).

The accident data mode is the more appropriate when historical data is available because it will then directly compare the differences between variable speed and fixed speed systems. There are, however, two problems with that mode: data is seldom available on fixed speed systems by weather conditions; and, actual data is not available from the variable speed prototype system in the short term. Until significant historical accident data is available from the prototype, this model may be used more simply by entering the projected mean speed and standard deviation. The model will then project the cost data based on those two parameters. Limitations of such use of a model are typical of all other projections: The results are usable to the degree to which the input parameters reflect the real world. As of the date of this report, driver response to the prototype has not stabilized sufficiently for accident data to be valid. Therefore, use of the model in the projected accident rate mode may be more appropriate in the near term.

The Secretary of the U.S. Department of Transportation recently issued a report entitled, "Interim Safety Consequences of Raising the Speed on Rural Interstate Highways."[1] It is the term, "reduced accidents and delays" that forces the consideration of the existing and realistic fixed speed limit systems.

The model, as delivered, can be used to compare variable speed limit systems to either fixed existing or fixed realistic speed systems by altering the input data to match either actual or projected attributes of those systems. No further distinction between these two fixed speed systems will be contained in this paper.

SECTION TWO
BASIC RELATIONSHIPS

The basic mathematical relationships for the fixed speed - existing and variable speed systems will be described in this section.

In this report the following notation is used:

FSE = Existing Fixed Speed - 55 or 65 mi/h
FSR = Realistic Fixed Speed - 65 mi/h or greater
VS = Variable Speed - (less to 65+)
TC = Total Cost
SC = System Costs (Variable or Fixed Speed Equipment)
AC = Accident Costs
AIDC = Accident-Induced Delay Costs
TTC = Traverse Time Costs

The total cost of a speed limit system is the cost of the signs and their maintenance plus the cost of accidents plus the accident-induced delay costs plus the cost of the time vehicles (and their occupants) spend traversing that system. Benefits are established by comparing a VSL system to a fixed speed system. The net difference between the costs of the two systems is the benefit.

The basic cost function is:

Total Cost = SC + AC + AIDC + TTC

Because traverse time costs may be a function of the speed, three different speed limit systems are relevant to this discussion:

- o Fixed speed systems with their existing lower limit (55 or 65) are relevant since the traverse time cost may be compared to a variable system that could have higher speed limits (and lower traverse time costs) under ideal conditions.

- o Fixed speed systems with realistic speeds are relevant under the hypothesis that higher speed limits trigger more accidents (under less-than ideal conditions) and result in more serious accidents.

- o Variable speed limits which provide the reduced traverse time costs during ideal conditions and, possibly, reduced accidents during less-than-ideal conditions.

The costs for these three systems could be represented in the following equations:

TC(FSE) = SC(FSE) + AC(FSE) + AIDC(FSE) + TTC(FSE)
TC(FSR) = SC(FSR) + AC(FSR) + AIDC(FSR) + TTC(FSR)
TC(VS) = SC(VS) + AC(VS) + AIDC(VS) + TTC(VS)

The benefit cost model developed in this effort used the following difference equation as its basis:

Total Difference = (SC(FSE)-SC(VS)) - (AC(FSE)-AC(VS)) - (AIDC(FSE)-AIDC(VS)) - (TTC(FSE)-TTC(VS))

The installation and maintenance costs on existing fixed signs is assumed to be insignificant. The difference between the system cost for the fixed speed system and the variable speed system will therefore be 100 percent of the variable speed limit production cost, installation costs and operational costs.

SECTION THREE
ASSUMPTIONS

ASSUMPTIONS AND DATA SOURCES

A variety of assumptions have been made in the process of developing the variable speed limit cost benefit model. These can be divided into general and initial assumptions. General assumptions will be simply stated. Initial assumptions will be explained in more detail and sources specified, where available. It is important to note that the model's developers were not advocates for most of the assumptions. Rather, the assumptions represent a set of logical conditions defined by the authors within which the model is a representation of some level of reality. The better the assumptions reflect actual conditions, the better the model's accuracy in forecasting the actual cost and benefits that may be achieved.

GENERAL ASSUMPTIONS

Driver speed decisions have two components: (1) risk of accident involvement vs. arrival time and (2) compliance (or noncompliance) with speed limit vs. arrival time. Differential speed cost in fuel consumption, vehicle wear and tear and driver fatigue are outside the scope of this model.

The involvement rate per 1,000,000 vehicle miles (MVM) for fixed speed existing systems is a function of driver's response to road conditions.[2]

Drivers will respond to realistic variable speed limits and associated variable message warnings by altering their speed in a manner which reduces the speed variance and results in lower accident involvement rates. The model will accept any range of involvement rates but its development was based on the expectation that actual data will support the above assumption.

Linked VSL systems will provide benefits, in addition to the isolated VSL configuration, in the form of lower involvement rates than isolated VSL systems because of the upstream warning feature.

The value of the motorists' time is significant. An initial assumption of $10 per hour has been used.

Traverse time cost, the elapsed time spent traversing a segment of highway multiplied by the value of time (initial value = $10 per hour), represents as real a cost as accident costs. Elimination of this factor from the equation (and the model) would imply a value of time equal to $0 per hour for traverse time.

The value of time for commercial vehicles is not significantly different than passenger vehicles. Note: This assumption is known to be incorrect but further complexity was outside the scope of this effort. This incorrect assumption is listed here to invite further development to correct the model's understatement of the value of time for commercial drivers and the time value of their cargo.

Accident induced delays can be simply expressed as a time period during which one direction of the flow past an accident site stops for the duration of the accident delay period.

Condition sensitive involvement rates as described by Bellomo-McGee, Inc. [2] represent an alternative involvement estimator to the deviation from mean speed projection process. Other research [3] shows that only a small difference in involvement rates exists for the intervals mean with SD +/- 5 mi/h and mean with SD +/- 15 mi/h. Since traffic flows with standard deviations larger than +/- 15 mi/h are rare, driving condition sensitive involvement rates represent an alternative method of expressing accident rates to Solomon's mean speed and standard deviation system. The model will accept either the condition sensitive involvement rates or the mean speed and standard deviation as input values.

Variable speed limit highway segments could have a higher speed limit - under ideal conditions - than a fixed speed limit system. If analysis of variable speed limit systems is constrained to the maximum speed of fixed limit systems, the true potential value of the variable speed limit system may be vastly understated.

Historical data on variable speed limit highways segments will have higher average speeds because motorists will drive faster in response to higher legal speed limits during the two thirds of the driving time with daytime, dry conditions. Based on this assumption, the model's initial mean speed for VSLs will be higher than for the FSE.

INITIAL ASSUMPTIONS

The initial assumptions are organized by the order in which the data elements are encountered in the basic equations in section 2. There is also a reference to the spreadsheet range in which the user would change the data should different assumptions be considered by a model user. The use of the Lotus 1-2-3 range function is explained more fully in section 6.

VSL system costs will be the same as those encountered by Farradyne Systems, Inc. (FSI), in the prototype. (These are shown in spreadsheet range designated VSLCOST.)

Involvement rates for Fixed Speed Limit - Existing system will be the same as those shown on the State of New Mexico, Department of Motor Vehicles' report entitled, Accidents by Administrative Route for the years 1985 through 1987 for I-40 from mile 63 to mile 117.[4] Rain was assumed to be the prevailing condition when "speed for conditions" was entered in the Contributing Factors column. The involvement rate was calculated using the Annualized Daily Traffic (ADT) and the distance to calculate the millions of vehicle miles over 3 years. The number of vehicles involved was taken from the column marked "TRAV." Fatalities and injuries were taken from the columns so marked and were calculated as a percent of the total involvements. Day and night accident separations were done on the following basis: From October through February, night was defined as 19:00 to 05:30; from March through August, night was defined as 17:00 to 07:00. The rates developed by this method were loaded into the INVOLV Range.

Involvement rates for Isolated VSL systems will be at least 4 percent lower than those of the fixed limit - existing system. Note that the model as delivered contains a feature to automatically fill in the VSL involvement rate at 96 percent of the fixed limit - existing rates. When historic data is loaded into the involvement table (range:INVOLV), this action will overwrite the 96 percent calculation and the model will display results based on that historic data. The user can enter other data or modify the formulas to produce other differences.

The model developers only provided these percent reductions to test the model's benefits calculations. The scope of this effort contained no feature to warrant research to support any specific involvement reduction level.

The involvement rate for linked VSL system was assumed to be at least 6 percent lower than those of the fixed limit - existing system because of the additional potential benefit of the upstream warning feature.

Note that until historic data is input, the benefits shown are only a reflection of that very broad judgement about driver response to variable speed limit systems. Increasing these percentages will increase the benefits shown; decreasing them will reduce the benefits shown.

The average speed (mean speed) of VSL systems will be at least 2 mi/h higher than those of a fixed speed - existing system. This is based on the expectation that VSL systems will have higher speed limits under daytime dry conditions than a fixed limit system. The variable message feature of the VSL system could be used to suggest the minimum risk speed to encourage slower drivers (55 mi/h by habit) to increase their speed, thus reducing their exposure to being overtaken. Speed data is entered in range:SPEED.

The cost of each fatality involvement has been initially set at \$1,450,000.[5] The model will accept other input values. See range:PARMS.

The cost of each injury has been set at \$11,000 per involvement. The model will accept other input values. See above and range:PARMS.

The cost of property damage only has been set at \$2,000 per involvement. See above and range:PARMS.

The ratio of the ADT exposed to day and night conditions was assumed to be 2.5:1 based on an analysis of the hourly ADT for I-70 in Maryland.[6] See range:COND.

The allocation of ADT exposure to dry and wet highway conditions was done by making the assumption that in the Middle Atlantic region, the duration of rainfall on rain days was 3 hours. Attempts to obtain better data through the National Weather Service proved fruitless. Although they collect the amount of rain by the hour, data on the hours of rainfall is not conveniently available. A similar assumption was made for Albuquerque: Rainfall duration was assumed to be 1 hour. These assumptions seem reasonable yielding an average rainfall rate of 0.15 in per hour for I-40. The I-70 average rainfall rate based on the 3 hours duration assumption is 0.10 in per hour. By assuming that the rainfall is equally spread between night and day, the total I-40 ADT exposure to conditions is 71 percent, 28 percent, 0.7 percent, 0.3 percent for day dry, night dry, day wet, night wet respectively. For I-70 the exposure rate is 69 percent, 27 percent, 3 percent, 1 percent in the same sequence. These data were used to determine the millions of vehicle miles that become the denominator in involvement rate calculations. See range:INVOLV.

The Accident-Induced Delay (more accurately, the Involvement-Induced Delay) calculation assumes that all of the traffic in the direction of the accident is blocked for the induced delay period. For simplicity sake, each direction is assumed to be half of the flow for duration. The delay period has been initially set at 30 minutes (0.50 hours) per accident. Since the model's calculation units use involvements, the factor of involvements/accident is necessary to compute the final accident-induced delay costs. Based on the I-70 data, this initial value is 1.58 involvements/accident. See range:PARMS.

The value of time has been set at $10 per vehicle hour. A study indicates $16 per vehicle hour but $10 was used initially to assure that the model initially erred on the conservative side.[7, 8] (See the range:PARMS.)

SECTION FOUR
CONFIGURATIONS

CONFIGURATIONS USED IN VARIABLE SPEED LIMIT STUDY

This section will describe the four configurations used in this cost benefit model. For each configuration the geometry, traffic, weather and hardware will be described.

ISOLATED RURAL CONFIGURATION

Geometry

Proposed Location: I-40 West of Albuquerque NM.
First Interchange: Prewitt at milepost 63
Last Interchange: Mesita at milepost 117
Number of Interchanges: 12
Total Length (2 directions): 108 miles
Average Interchange Spacing: 4.9 miles

Traffic

Number of Lanes: 2
ADT: 10,000 to 12,500

Weather

Annual Rainfall: 12.08 in
Annual Number of Rainy Days: 76
Annual Snowfall: 10.6 in
Annual Number of Snowy Days: 5

Hardware

System Operating Mode: Isolated
Number of Stations: 24
Communications Media: none
Feet of Conduit - Soft Ground: 12,000
Feet of Conduit - Pavement/Concrete: none

LINKED CONFIGURATION

Geometry

Proposed Location: I-70 Centered around Frederick, MD.
First Interchange: Exit 42
Last Interchange: Exit 62
Number of Interchange: 9
Total Length (two directions): 36
Average Interchange Spacing: 2 miles

Traffic

Number of Lanes (each direction): 2
ADT: 30,000 at the ends, 40,000 at Frederick

Weather

Annual Rainfall: 37.7 in
Annual Number of Rainy Days: 119
Annual Snowfall: 8.6 in
Annual Number of Snowy Days: 3

Hardware

System Operating Mode: Linked
Number of Stations (two directions): 18
Communications Media: Radio
Feet of Conduit - Soft Ground: 9000
Feet of Conduit - Pavement/Concrete: 1800

INTEGRATED CONFIGURATION

Geometry

Proposed Location: SCANDI System in Detroit, MI.
First Interchange: See Detroit map
Last Interchange: See Detroit map
Number of Interchange: 25
Total Length (two directions): 60 miles
Average Interchange Spacing: 1.2 miles

Traffic

Number of Lanes (each direction): 3 or 4
ADT: 112,000

Weather

Annual Rainfall: 26.27 in
Annual Number of Rainy Days: 137
Annual Snowfall: 38.7 in
Annual Number of Snowy Days: 14

Hardware

System Operating Mode: Integrated with Freeway Management System

Number of Stations (two directions): 50

Communications Media: Wire

Feet of Conduit - Soft Ground: none

Feet of Conduit - Pavement/Concrete: 2500

INTEGRATED CONFIGURATION WITH IN-VEHICLE DISPLAY

Geometry

Proposed Location: SCANDI System in Detroit, MI.

First Interchange: See Detroit map

Last Interchange: See Detroit map

Number of Interchange: 25

Total Length (two directions): 60 miles

Average Interchange Spacing: 1.2 miles

Traffic

Number of Lanes (each direction): 3 or 4

ADT: 112,000

Weather

Annual Rainfall: 26.27 in

Annual Number of Rainy Days: 137

Annual Snowfall: 38.7 in

Annual Number of Snowy Days: 14

Hardware

System Operating Mode: Integrated with Freeway Management System
Number of Stations (two directions): 50
Communications Media: Wire plus radio for transmission to the vehicle
Feet of Conduit - Soft Ground: none
Feet of Conduit - Pavement/Concrete: 2500

NOTE: The in-vehicle display configuration is the same as the integrated system except for electronic signposts at each variable speed limit station. These signposts will transmit data to each vehicle in its proximity. The system will be able to select the data to be transmitted by the direction of the vehicle. The data to be transmitted will be the same as on the variable speed limit sign.

SECTION FIVE
ACQUISITION AND MAINTENANCE COSTS

VARIABLE SPEED SYSTEM ACQUISITION AND MAINTENANCE COSTS

The hardware and software contained in the variable speed limit system is described in a report by Farradyne Systems, Inc.[9]

That report contains the following descriptions:

- Loop Installation.
- Foundations.
- Poles.
- Power Connection.
- Signs.
- Processors.
- Communications (wire or radio).
- In-vehicle display.
- Annual maintenance.
- Annual depreciation.

The costs shown in the model range VSLCOST represent preliminary data. Since the equipment was installed in the summer of 1988, the costs in the December report are not expected to diverge significantly from the preliminary costs.

SECTION SIX
DESCRIPTION OF THE MODEL

DETAILED DESCRIPTION OF THE MODEL

For efficiency in moving around this large model, the Lotus 1-2-3 range definition function was used. Each of the ranges in the model will be described in this section. The ranges are: SYSCON, SUMMARY, VSLCOST, PARMS, COND, INVOLV, SPEED, STDDEV, FATCOST, INJCOST, PDOCOST, AIDCOST, TRAVCOST, \0, \S, \Y, MENU, FITCURVE, CURVE1, CURVE2, CURVE3, CURVE4, AND INTRO. To access these cells, the user hits F5, then types the range name, then hits Enter/Return. These ranges include all the cells of the model. When these ranges are printed using the Lotus print function, they are referred to in the text as tables.

A range-by-range explanation has been developed in place of a cell-by-cell description because the use of ranges is much more user friendly than cell addresses. Each range description does include the cell addresses for cross reference purposes.

SYSCON - CELLS A15-L40

This range provides title and descriptive information on each of the 4 configurations plus some limited user instructions. All of this information can be changed.

SUMMARY - CELLS DT15-EM42

This range shows the results of all of the calculations. It is, in effect, the answer to the question, "Are variable speed systems cost effective when compared to fixed speed systems?" The columns show types of costs and the rows show the fixed and VSL costs for each of the 4 configurations. Note that this table shows the results of the calculations and therefore, cannot be changed without altering the integrity of the model. Any change to the data by the model user will be reflected on this page.

VSLCOST - CELLS A40-L67

This table is the primary input tool for the variable speed limit system costs. For each of the 13 rows there is a description of the hardware item, a unit cost for that item, and the number of units of that item required for each VSL interchange configuration. Note that either a small sign or a large sign is required by each interchange -- but not both. Also note that neither the rural isolated nor the linked system use Communications (wire) but that the "1" in the Communications (radio) column indicates that the linked configuration does use one $3,500 radio for each station (2 per interchange). The cost of the conduit and the distance for each interchange are also included.

The user may change any of the costs or, if the configuration warrants, increase the number of feet of conduit required for the interchanges.

The "percent Annual Maintenance Cost" is initially set at 15 percent of the initial purchase value. The "Annual Deprecation-Lifetime(yrs)" is 10 percent of the total initial purchase for each of 10 years. The Annual Cost (per station) is the sum of the maintenance and the depreciation costs. The "Annual Cost (per system)" is the Annual Cost (per Station) times the "Number of Stations" from the SYSCON range.

All of the data shown on the SYSCON range is per station. The one-time capital outlay for the entire system can be determined by multiplying the "Cost" line by two times the number of interchanges.

The annual maintenance cost for the entire system can be determined by multiplying "percent Annual Maintenance Cost" line by two times the number of interchanges.

PARMS - CELLS P8-T35

The PARMS range is the input device for the cost and involvement rates. "Value of time in Dollars/Veh-Hr" is expressed in terms of the vehicle per hour.

It understates the value of commercial vehicles and multipassenger trips. But this value does not consider that nighttime and weekend traffic may have a different value than weekday traffic. The model has been shown to be sensitive to this value.

"Dollars/Fatal Involvement" is the measure of human life cost.

"Dollars/Injury Involvement" is the measure of value of an injury involvement.

"Dollars/Property Damage Only Involvement" is the cost of fender benders.

"Accident-Induced Delay Period in Hours" expresses the amount of time that the roadway is blocked because of an accident. The initial value of 0.5 hours means that the roadway is blocked in one direction for an average of 30 minutes for each accident. All traffic in that direction is blocked for that period. This measure does not account for traffic passing by an accident in another lane, nor does it consider the time required for any traffic backup to dissipate.

"Factor of Involvements per Accident (INV/ACC)" is the model's conversion factor from involvements to accidents. There can be one or many involvements per accident. The model uses this figure to convert the involvement rate to an accident rate for which accident-induced delay periods will be directly related. This is the proper conversion since the accident is the event which causes the delay.

"Percent of Total Involvements - Fatal" represents the percent of total involvements that result in fatalities. It is the number of fatalities divided by the total number of vehicles involved in accidents. The model has been shown to be sensitive to this number.

"Percent of Total Involvements - Injury" is the total injuries divided by the total involvements.

"Percent of Total Involvements - Property Damage Only" is the remaining percent of involvements that are not fatal or injury.

All of the data in this range can be altered by the user. As noted above, the model results are sensitive to the value of time, the cost of fatalities and the rate of fatalities.

COND - CELLS P36-V74

The "COND" table is the primary input tool for the environmental conditions to which traffic is exposed during the year. While four conditions are typical of the what the model user would input, up to 12 conditions can be handled. However, since engineers responsible for some specialized environments (such as coastal highways subject to sudden fog) may have high interest in this model, visibility is specified for each of the possible conditions. The user must specify the percent of the ADT exposed to each of the conditions.

One special case of conditions is "composite" conditions which allows the user to express all of the traffic as being exposed to an average set of conditions. Users should enter 100 in the "percent exposure" column for this row when using the model in the mean speed and speed variance mode.

If the user's entries in the "percent exposure" column does not add up to 100 percent, an error message is displayed on the range:Summary page.

INVOLV - CELLS V36-AH71

This table is the primary tool for user input if actual data is available. The data is to be input in units of involvements per 1 million vehicle miles. The "Fixed1" and "Fixed2" columns contain the actual data received from the configurations selected. For example, the Fixed2 column contains data obtained from the Maryland Department of Transportation for I-70 near Frederick. In the column marked "Condition Number" in the row marked "1", the number 0.51 under "Fixed2" means that the actual involvement rate for that highway for daytime, unlimited visibility, no precipitation was 0.51 involvements per 1,000,000 vehicle miles during the years from 1985 through 1987. Likewise the night, unlimited visibility, no precipitation rate was 0.91 involvements per 1,000,000 vehicle miles on that section of highway.

When data becomes available on the involvement rates for variable speed systems, these can be entered into the model in this table. When data is available from the prototype, judgments will have to be made to extrapolate the driver response to the prototype, to other configurations such as I-70 in Maryland. If the involvement rate on the prototype decreases after the variable speed limit system is operational, then the same effect could be projected for other configurations by adjusting the involvement rates on this table.

SPEED - CELLS AH36-AT71

The SPEED range is the primary input tool for the users to enter vehicle speed data. Since the model has been shown to be sensitive to the traverse time cost, this table is important to the results. If there is no speed difference between the fixed speed system and the variable speed system, the benefits from the system on traverse time costs will be small. If, as described in the assumptions, the variable speed limit system is allowed to have higher limits during ideal conditions, then the mean speed difference will represent a significant benefit from the highway user's standpoint.

All of the data on this range can be changed by the user.

STDDEV - CELLS AT35-BF71

The STDDEV range is the input tool for the standard deviation data for each of the configurations. When it is used, the only row that it should be entered is the last row marked with the symbol "*" meaning composite. This data will be used to calculate the involvement rate for each of the configurations.

Data entered into the rows marked "1" through "12" are ignored when the number 100 is entered into the composite row on COND range table.

FATCOST - CELLS BF36-BR73

The FATCOST table presents the calculated cost of fatalities for each of the configurations by multiplying the ADT times the miles of roadway times 365 days, dividing by 1,000,000 to get millions of vehicle miles and multiplying that product by the involvement rate and that product by the fatality rate and the dollars/fatal involvement. For example, on I-70, the 32,000 ADT times the 36 miles times 365 days gives 420,480,000 vehicle miles. That divided by 1,000,000 give 420.48 million vehicle miles which when multiplied by 0.763 involvements per million vehicle miles and by 0.0124 fatalities per involvement gives 3.98 fatalities per year. That number multiplied by $1,450,000 per fatality gives $5,780,552 as the cost of fatalities per year. In the condition sensitive mode, the model calculates the fatality costs for each of the conditions depending on the exposure rate to each condition and then totals them up. The fatality costs for each condition are shown in this range. In the standard deviation mode, a composite calculation is made and only the thirteenth row marked by "*" for composite and the total line of this range will contain data.

Since this table shows the results of calculations, it is not correct for the user to change this data.

INJCOST - CELLS BR36-CD73

The INJCOST table present the calculated cost of injuries for each of the configurations by multiplying the ADT times the miles of roadway times 365 days, dividing by 1,000,000 to get millions of vehicle miles and multiplying that product by the involvement rate and that product by the injury rate and the dollars/injury involvement - Injury. For example, on I-70, the 32,000 ADT times the 36 miles times 365 days gives 420,480,000 vehicle miles. That divided by 1,000,000 give 420.48 million vehicle miles which when multiplied by 0.763 involvements per million vehicle miles and by 0.494 injuries per involvement gives 158.82 injuries per year. That number multiplied by $11,000 per injury gives $1,747,026 as the cost of injuries per year. In the condition sensitive mode, the model calculates the injury costs for each of the conditions depending on the exposure rate to each condition and then totals them up. The injury costs for each condition are shown in this range. In the standard deviation mode, a composite calculation is made and only the thirteenth row marked by "*" for composite and the total line of this range will contain data.

Since this table shows the results of calculations, it is not correct for the user to change this data.

PDOCOST - CELLS CD36-CP73

The PDOCOST table presents the calculated cost of property damage only for each of the configurations by multiplying the ADT times the miles of roadway times 365 days, dividing by 1,000,000 to get millions of vehicle miles and multiplying that product by the involvement rate and that product by the dollars/property damage only involvement. For example, on I-70, the 32,000 ADT times the 36 miles times 365 days gives 420,480,000 vehicle miles. That divided by 1,000,000 give 420.48 million vehicle miles which when multiplied by 0.76 involvements per million vehicle miles and by 0.4935 PDO per involvement gives 157.5 PDOs per year. That number multiplied by $2,000 per PDO gives $317,384 as the cost of PDOs per year. In the condition sensitive mode, the model calculates the PDO costs for each of the conditions depending on the exposure rate to each condition and then totals them up. The PDO costs for each condition are shown in this range. In the standard deviation mode, a composite calculation is made and only the thirteenth row marked by "*" for composite and the total line of this range will contain data.

Since this table shows the results of calculations, it is not correct for the user to change this data.

AIDCOST - CELLS CP36-DB73

For this model, the number of vehicles delayed for each involvement is the number of vehicles in one direction which would have passed the point where the accident occurred during the specified delay period. This is vehicles/day divided by 24 to get vehicles/hour multiplied by 1/2 to get the one direction

ADT all multiplied by the delay period in decimal hours. This number is (32000/(24*2))*.5) which equals 333.3 delayed vehicles for each accident. The final term to calculate is the $/involvement. Multiply the $/vehicle-hour by the number of delayed vehicles and the delay period in decimal hours. This number is $10*.5*333.3 which equals 1666.7 $/incident. The cost per year for the accident induced delay may now be calculated by multiplying the incidents/year by the $/incident to get $/year. (I-70 had 203 incidents involving 321 vehicles). This number is (321 divided by 1.58 to get) 203 incidents (accidents) times $1666.7 which equals an annual accident induced delay cost of $338,342.

In the condition sensitive mode, the model calculates the accident-induced delay costs for each of the conditions depending on the exposure rate to each condition and then totals them up. The accident-induced delay costs for each condition are shown in this range. In the standard deviation mode, a composite calculation is made and only the thirteenth row marked by "*" for composite and the total line of this range will contain data.

Since this table shows the results of calculations, it is not correct for the user to change this data.

TRAVCOST - CELLS DB36-DN73

This range, TRAVCOST, is a very significant factor. It is the millions of vehicle miles per year divided by the mean speed and multiplied by the cost of time. In the I-70 example, the 420,480,000 vehicle miles are divided by the mean speed from the speed range 59.5 giving a quotient of 7,135,924 hours which, when multiplied by $10 per hour equals about $71 million per year. This is a major cost to the model. The user cannot directly change any of the calculation results in the TRAVCOST range. Changes must be made in the mean speed or the value of time to change the results.

It should be noted that any of the formula in the spreadsheet could be modified should different relationships warrant such a change.

LOTUS MACRO FUNCTIONS

The following Lotus macro functions will be active:

\0 - Cells B72-B72
\S - Cells B74-B78
\Y - Cells FZ12-GB30
MENU - Cells FZ2-GA4

When the model is loaded into LOTUS 1-2-3, the user will be asked to choose either the Manual INVOLVEMENT Entry option or the Automatic INVOLVEMENT Entry option. The \0 macro facility in 1-2-3 is used to call the \S macro when the model is loaded. The \S macro sets up the command menu using the MENU range which prompts the user to choose an option. When the Automatic INVOLVEMENT Entry option is chosen, the \S macro branches to the \Y macro. The \Y macro will place the involvement rates calculated from the ranges described below into the composite row of the INVOLV table. In addition, the condition rates for all conditions (rows 1-12) are blanked and the rate for the composite row is set to 100 percent. When the \Y macro has completed, control is passed back to the \S macro. The \S macro will terminate after moving the user to the INTRO range and control is returned to the user.

When the Manual INVOLVEMENT Entry option is chosen, the \S macro terminates normally without branching after moving the user to the INTRO range. This option will suppress the automatic entry of the model-calculated involvement rates and preserve the current contents of the INVOLV table and the Exposure Rate table.

FITCURVE - CELLS FA1-FD80

This range represents the curve fitting data which is used in the ranges described to calculate the involvement rate in million vehicle miles based on a standard deviation from mean speed figure. The development of the relationship between the involvement rate and the standard deviation from mean speed was based on the assumption that Solomon's curve is largely independent of the mean speed. In this range, Solomon's curve is fitted to an expression given by:[10]

$$I = k(v-t)^2 + R$$

where,

I = involvement rate in 100 million vehicle-miles
k = constant
v = difference between mean speed and given speed
t = the difference between the mean speed and the speed where the involvement rate is a minimum
R = the minimum involvement rate given by Solomon.

The best curve fit was obtained by varying k until the sum of the absolute difference between the common data points of the fitted curve and Solomon's curve were a minimum. The v term is the first data column in this range and is given for integer miles per hour from 30 mi/h below the mean speed to 30 mi/h above the mean speed. The second column is the data fitted to the Solomon curve expressed by I for each v.

The FITCURVE range contains the reference data from which the following ranges are calculated. It is not correct for the user to change this data.

CURVE1 - Cells FF1-FI80
CURVE2 - Cells FK1-FN80
CURVE3 - Cells FP1-FS80
CURVE4 - Cells FU1-FX80

These four ranges contain the data which is used to calculate the involvement rate based on Solomon's curve and the standard deviation input from the composite row of the STDDEV table. For each of the four ranges, the first and third columns contain the data which represents a normal distribution about a mean speed for the fixed speed limit system and the variable speed limit system respectively. These normal distributions are given by the standard expression (e) raised to a (-x) power where:

$$x = (v^2 / (2S^2)) / ((\sqrt{2\pi})(S))$$

and,

v = difference between mean speed and given speed

S = standard deviation.

The second column in each of the four ranges is the product of the column to its left (the first column) and the column in the FITCURVE range defined by I. Then for each row of v, the percent of the total vehicles which are traveling at a speed v is multiplied by the involvement rate I. Since Solomon's data is expressed in terms of 100 million vehicle-miles, the involvement rate for each v is divided by 100 to give the involvement rate per 1 million vehicle-miles which are the units defined by the INVOLV table. The sum of the second column is the composite involvement rate for the fixed speed limit system.

The fourth column in each range is related to the third column in exactly the same way. The sum of the fourth column is the composite involvement rate for the variable speed limit system.

Since the only variable input to these ranges is drawn from the STDDEV table, it is not correct for the user to change this data.

INTRO - CELLS B80-G125

This range contains information about the model developers and a brief description of the ranges defined in the model.

SECTION SEVEN
COST BENEFIT MODEL RESULTS AND SENSITIVITIES

PRELIMINARY MODEL RESULTS AND SENSITIVITIES

This section presents the preliminary results of the cost benefit analysis and the sensitivity of the results to a variety of input values.

MODEL RESULTS

When the traffic and environmental characteristics for Interstate 40 west of Albuquerque, New Mexico are entered into the model, **based on the assumptions in section 3,** the results show an annual cost of $85,800 over 10 years and provide an annual benefit of $3,162,480. The one-time capital costs (from Range:SYSCON) are $14,300 per station (2 at each interchange = $28,600; 12 interchanges = $343,200). The annual maintenance cost for I-40 is $2,145 per station ($51,480 for 12 interchanges). The benefit to cost ratio is 37 to 1.

The same set of projections for a linked VSL system on Interstate 70 near Frederick, Maryland have an annual cost of $127,125 over 10 years and provide an annual benefit of $2,834,067. The one-time capital costs (from range:SYSCON) are $28,250 per station (2 at each interchange = $56,500; 9 interchanges = $508,500). The annual maintenance cost for I-70 is $4,238 per station ($76,284 for 9 interchanges). The benefit to cost ratio is 22 to 1.

The same set of projections for an Integrated VSL system on SCANDI System in Detroit, Mich. have an annual cost of $285,938 over 10 years and provide an annual benefit of $15,774,704. The one-time capital costs (from range:SYSCON) are $22,875 per station (2 at each interchange = $45,750; 25 interchanges = $1,143,750). The annual maintenance cost for SCANDI is $3,431 per station ($171,550 for 25 interchanges). The benefit to cost ratio is 55 to 1.

The same set of projections for an In-Vehicle VSL system on SCANDI System in Detroit, Mich. would differ form the Integrated VSL with the inclusion of a

$2,500 roadside radio transmitter for the In-vehicle display unit at each station. The In-Vehicle system would have an annual cost of $317,188 over 10 years and provide an annual benefit of $16,828,105. The one-time capital costs (from range:SYSCON) are $25,375 per station (2 at each interchange = $50,750; 25 interchanges = $1,268,750). The annual maintenance cost for In-Vehicle VSL is $3,806 per station ($190,300 for 25 interchanges). The benefit to cost ratio is 53 to 1.

It must be noted again that these results are projected where historical data is lacking. This is particularly true with respect to the drivers' response to the variable speed limit System.

SENSITIVITY ANALYSIS

In this section the model's response to varying input will be examined to guide decision makers towards informed use of the model's results.

Basic Approach

There are two basic approaches to sensitivity analysis. The first is the Inspection Method. With this method, the model's output, based on its initial inputs, is inspected to see which components had the most impact on the results. These inputs are then examined in detail, their reasonableness carefully examined, and their range determined. The model is then re-run using a variety of ranges of these important inputs while less significant inputs are held constant. This is appropriate for simple models like this variable speed limit cost model (VSLCM).

The other method, the Systematic Exercise Method, is frequently used on complex models where many variables and complex functions are involved. With this method, each input is varied through a range of values while the others are held constant. The results and nonlinear changes in the results are carefully analyzed. This type of sensitivity analysis is not indicated for this variable speed limit cost model.

Analysis of Initial Results

Initial analysis of the VSLCM initial results indicates that the fatal accident costs and the traverse time costs are much higher than the system costs, the injury accident costs, the PDO costs and the accident-induced delay costs.

Analysis of Fatality Costs

Fatality costs are calculated using the ADT and the actual involvement rates obtained from the States of New Mexico and Maryland. Small changes in the fatality rate used between systems under comparison could completely change the cost benefit relationship.

For example if the initial fatality rate for I-70 is changed from 1.24 percent per involvement to 2 percent, the cost of fatalities jumps from $ 5,780,552 to $9,323,470. Unfortunately, as of October 1988, there is no real data to justify the use of different fatality rates between the fixed limit existing system and a variable speed system. This is particularly true since more than one half of the fatalities involve alcohol-related accidents. It was the judgement of the operations managers at two variable speed system sites that their systems had little effect on the drinking drivers. Until actual data is available, the value of the results of this model will be limited with respect to fatal accident costs.

Traverse Time Costs

Traverse time costs represent a very different situation with respect to model sensitivity. In the linked configuration, a 2 mi/h increase in the mean speed changes the annual traverse time costs from $71,359,247 to $69,016,179 (more than $1 million per mile per hour in annual costs). This figure is known to be understated in that it assumes $10 per hour for all vehicles.

The source of the initial cost per vehicle hour ($10) was reference 8. This report suggested a cost of $14 per vehicle hour. The $10 figure was used to err on the conservative side. But this study updated an earlier study that estimated truck drivers time at $20 per hour. This analysis did not, however, include the time value of the merchandise on the commercial vehicles. A more realistic figure for the time value of a truck, its driver and cargo may be as high as $100 per hour. This is just a guess as actual determination is outside the scope of this study.

If truck traffic is included and assumed to be 20 percent of the total, and if $100 per hour is used for the value of commercial vehicle per hour, then the composite rate per hour jumps to $28 per hour per vehicle.

The annual traverse time cost for the linked configuration changes from $70 million to $196 million. A 1 mi/h difference in the average speed between two systems under comparison would then result in a benefit of about $3,000,000. With potential benefits of this magnitude several conclusions are various obvious.

Sensitivity Analysis Conclusions

The traverse time costs should be more carefully analyzed with respect to two factors: composition of vehicular traffic with respect to cost and the effective weight of public officials' response to traffic fatalities.

The composition of traffic analysis should include the actual composition of the traffic with respect to time value on the each of the scenarios. Also the American Trucking Association should be contacted to determine the time value of an average commercial vehicle. The model should then be exercised using a more realistic time cost.

Since the fixed speed existing system had reduced (imported) fuel costs as its original goal, the model should be enhanced to include the off setting increased air resistance and fuel consumption at higher mean speeds. Not only would this balance the traverse time costs, but the use of the higher time value could thus be justified.

Public officials and transportation planners are subject to many pressures and much research has been done on the various fixed speed limit options. Clearly speed limits would be higher if cost were the only factor since traverse time costs are about 10 times higher than fatality costs.

SECTION EIGHT
RECOMMENDATIONS

Based on preliminary data, it is clear that variable speed limit systems provide decision makers with a **basis for further prototype installations of such systems.** The large potential savings from decreased traverse time costs while possibly decreasing the incidence of fatalities and injuries during unfavorable driving conditions, supports this position. With the additional data gathered by prototype systems, the model can then be re-run to verify the projected savings.

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