Economic Feasibility of Exclusive Vehicle Facilities

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A microcomputer program called "exclusive vehicle facilities" (EVFS) that determines the economic feasibility of separating light vehicles from heavy vehicles on a given section of controlled-access highway by designating existing lanes and constructing new lanes to be used exclusively by light or heavy vehicles is described. On the basis of user inputs to a spreadsheet user interface, EVFS calculates the net present value, benefit-cost ratio, and other performance measures of the alternative exclusive vehicle facility specified. The three possible lane use policies allowed within EVFS are mixed-, light-, and heavy-vehicle lanes. EVFS accounts for the following potential benefits or cost savings both for person and for freight travel: (a) travel time savings; (b) vehicle operating cost savings; and (c) accident cost savings (fatalities, injuries, and property damage), because of less severe accidents by separating light and heavy vehicles; and (d) queuing delay savings because of fewer accidents causing blockages. EVFS also accounts for the following project costs: (a) initial construction costs, (b) initial right-of-way acquisition and demolition costs, and (c) periodic pavement resurfacing costs, which may be less frequent and less costly for light-vehicle lanes. EVFS is designed to evaluate any of the following five cases: (a) do nothing; (b) designate existing lanes for mixed, light, and heavy vehicles; (c) add mixed-vehicle lanes (no special lane use restrictions); (d) add non-barrier-separated lanes and designate new and existing lanes for mixed, light, and heavy vehicles; and (e) add barrier-separated lanes and designate new and existing lanes for mixed, light, and heavy vehicles. An example indicates that exclusive vehicle facilities are most warranted for congested urban highways with significant percentages of single-unit and combination trucks in the traffic stream.

As vehicle size differences, vehicle volumes, and relative truck volumes continue to increase across the United States, the question arises as to whether exclusive vehicle lanes are economically warranted on a greater number of urban highways. Although the average automobile has become smaller and lighter, partly in response to fuel economy pressures, the average truck has become larger and is carrying greater loads as carriers strive to increase productivity. The average curb weight of new cars sold in the United States dropped from 3,600 lb in 1976 to 2,700 lb in 1982, and has ranged between 2,700 lb and 2,800 lb since then (L. Williams, personal communication). For all U.S. highways, truck vehicle-miles of travel (VMT) relative to passenger VMT has been increasing as trucks are carrying a greater share of all freight shipments. Percentages of total VMT accounted for by trucks and passenger vehicles were 28 and 72 percent in 1976, but changed to 22 and 78 percent by 1985. Over this same period, the share of total VMT accounted for by larger combination vehicles increased from 3.5 to 4.5 percent.

A general description and example application of an analysis program that determines the economic feasibility of separating light vehicles from heavy vehicles on limited-access highways by designating existing lanes and constructing new lanes to be used exclusively by light or heavy vehicles is described. On the basis of user inputs to a spreadsheet user interface, a microcomputer program called "exclusive vehicle facilities" (EVFS) calculates the net present value, benefit-cost ratio, and other facility performance measures for each alternative specified. EVFS was developed in research for the FHWA as part of its efforts to assess ways of improving the overall performance of the highway system.

The major potential benefits of exclusive vehicle facilities are (a) lower travel times caused by smoother traffic flow, (b) fewer fatal and nonfatal accidents per unit of travel because of vehicle size separation, and (c) less delay for both person and freight travel as a result of fewer and less-severe accidents causing lane blockages. Exclusive vehicle facilities are expected to be most warranted in major metropolitan areas, because the benefits of vehicle separation increase with overall traffic volumes and truck volume percentages in the vehicle mix. However, because construction costs per lane-mile are lower for rural at-grade highway sections with less developed right-of-ways than for elevated sections in densely built urban areas, exclusive vehicle facilities might also be economically feasible for certain rural highway sections with high accident rates because of truck-car interactions.

EVFS is designed for site-specific analyses and not for regional or national network analyses. EVFS can be used to evaluate reversible lane options by adjusting the inputs and outputs of EVFS to recognize that the reversible lanes serve only one direction of traffic for one-half of each day, including one peak period. Other recurrent traffic conditions, such as weekend recreational travel, can also be included by aggregating the results of several analyses for days of the year with different traffic volumes and vehicle mixes. EVFS is not applicable to toll roads, because fee schedule adjustments, special financing arrangements, tolls, user charges, and cost allocation issues are not considered. EVFS cannot be used to evaluate the cost effectiveness of high-occupancy-vehicle lanes, because passenger vehicles are not differentiated on the basis of automobile occupancy.

In comparing alternative vehicle facilities, EVFS accounts for differences both to person and to freight travel in (a) total travel time, (b) vehicle operating costs, (c) accident costs (fatalities, injuries, and property damage), and (d) accident travel time delays because of fewer and less severe accidents by

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separating light and heavy vehicles. EVFS also accounts for facility cost differences, including (a) initial construction, right-of-way acquisition and demolition costs; and (b) periodic pavement resurfacing costs, which may be less frequent and less costly for light-vehicle lanes.

The economic evaluation approach used in EVFS is to estimate and compare the net present values and benefit-cost ratios of alternative facility designs as generally prescribed for project investment analyses by engineering economic textbooks such as Au and Au (*1*). Many aspects of the cost and benefit calculations performed by the analysis program are described in the manual on benefit-cost analyses published by the Association of State Highway and Transportation Officials (also referred to as the "AASHTO Red Book") (*2*). All costs and benefits are calculated in 1985 dollars, and all future amounts are discounted to present values. Cost data obtained for other years are adjusted to 1985 dollars by applying the consumer price index (CPI) or more specific construction cost indices.

Three lane use policies allowed within EVFS pertain to mixed-vehicle (MV), light-vehicle (LV), and heavy-vehicle (HV) lanes. Heavy vehicles include the two categories of all single-unit (SU) trucks above 10,000 lb and all combination vehicles. Mixed-vehicle lanes can be used by all vehicles, subject to state and federal truck size and weight limits. Light-vehicle lanes can also be referred to as "car-only" lanes, and heavy-vehicle lanes can also be referred to as "truck-only" lanes. Light-vehicle lanes can only be used by motorcycles, automobiles, pickup trucks, light vans, buses, and trucks below 10,000-lb gross vehicle weight. All other vehicles must use the mixed- or heavy-vehicle lanes. Although buses are similar in weight and operating characteristics to SU vehicles, buses are permitted to use light-vehicle lanes for safety considerations of the bus occupants.

Vehicle separation can be achieved at a low capital cost by designating existing lanes for light vehicles only during peak travel hours. On the other hand, barrier-separated lanes have the highest capital cost because of more complex interchanges needed to separate traffic for access to and egress from the rest of the highway system. EVFS is designed to evaluate any of the following five cases:

- *Case 0:* Do nothing.
- *Case 1:* Designate existing lanes for mixed, light, and heavy vehicles.
- *Case 2:* Add MV lanes (no special lane use restrictions).
- *Case 3:* Add non-barrier-separated lanes and designate new and existing lanes for mixed, light, and heavy vehicles.
- *Case 4:* Add barrier-separated lanes and designate new and existing lanes for mixed, light, and heavy vehicles.

The purpose of evaluating Case 0 is to generate base-level estimates of facility performance to which the other alternatives can be compared. These base-level performance results also indicate whether input values describing a particular site are reasonable in terms of traffic speeds, travel times, and accident costs. The analysis of Case 1 may not be warranted where there are three or less existing lanes in each direction, but it may be an attractive alternative for sites with heavy truck traffic and four or five existing lanes in each direction. The Dan Ryan Expressway in Chicago is one example of Case 1 in which heavy vehicles were restricted from using the left-most of three lanes in each direction without adding any new lanes or traffic barriers.

Case 2 is the first alternative in which lanes are added to an existing facility. Case 2 is conventional highway widening with no lane use restrictions. Case 2 enables the user to generate baseline estimates of costs and benefits for a particular site given that a more typical capital improvement is made. Again, many of the inputs required for Case 2 will also be needed for Cases 3 and 4. Cases 3 and 4 both involve highway widening, but they are distinguished by whether the lanes carrying light and heavy vehicles are barrier separated, which adds greatly to the capital cost of lane and interchange construction. The New Jersey Turnpike for roughly 40 mi southwest of New York City is an example of Case 4 in which barrier-separated mixed-vehicle lanes were added and some of the existing lanes were restricted to light use.

All adjustable inputs needed to specify a particular facility alternative are entered to EVFS by a spreadsheet user interface and used by EVFS to make the engineering economic calculations needed to compare different alternatives. The spreadsheet user interface offers default values on the basis of nationwide averages for many of the input items, although the user has the option to override any of the default values with preferred values. EVFS also uses many data tables and formulas from a variety of sources referenced later such as the AASHTO Red Book (*2*) and the *1985 Highway Capacity Manual* (*3*) to evaluate traffic speeds and vehicle operating costs for the facility alternatives.

SITE AND TRAFFIC CHARACTERISTICS

As presented in Table 1, the spreadsheet user interface requires that the user specify general characteristics of the highway facility, traffic conditions, and surrounding area right-of-way. Highway construction costs and accident rates vary by whether a highway section is in a rural, suburban, or urban area. In EVFS, construction costs are assumed to be directly proportional to the total number of newly constructed lanes, and resurfacing costs are assumed to be proportional to the total number of new and existing lanes. Construction costs are higher for Case 4 in which the exclusive vehicle lanes are barrier separated. The curvature and gradient of a highway section affect its traffic capacity, average travel speeds and times, and vehicle operating costs.

Estimation of all user costs (value of time, vehicle operating costs, accident costs) and the resurfacing frequency requires knowledge of current and future traffic volumes, and the vehicle mixes in these traffic volumes. The user can either specify the current average daily traffic (ADT) for all lanes in the direction of traffic being analyzed and the average annual increase in this ADT, or specify current and future hourly traffic volumes for peak and off-peak periods, for which traffic volumes are always given for all lanes in the direction of traffic being analyzed.

Because EVFS does not include travel demand forecasting, the user must take into account the relative attraction or diversion of traffic to a highway because of more or less ca-

TABLE 1 FACILITY SPECIFICATION INPUTS TO EVFS

General Site Information:

1.	Is this a rural, suburban, or urban highway section R/S/U?	S
2.	Current mixed-vehicle lanes in each direction (0-6)?	3
3.	Future mixed-vehicle lanes in each direction (0-6)?	3
4.	Future light-vehicle lanes in each direction (0-6)?	2
5.	Future heavy-vehicle lanes in each direction (0-4)?	0
6.	Number of new lanes of right-of-way to acquire (0-4)?	2
7.	Will exclusive vehicle lanes be barrier separated (Y/N)?	N
8.	Length of section in miles (including decimal places)?	30.0
9.	Number of interchanges along this section?	5
10.	Average road gradient along section (typical value = 0%)?	0%
11.	Average curvature along section (typical value = 2 deg.)?	2

Press Enter

Traffic Characteristics:

		Defaults	
12.	Current average daily traffic (ADT) (one direction)?		80000
13.	Average annual increase in ADT (one direction)?		3000
14.	Current peak-period volume/hr (3 hours/day)?	6667	0
15.	Future peak-period volume/hr in 10 years?	9167	0
16.	Current off-peak volume/hr (15 hours/day)?	4000	0
17.	Future off-peak volume/hr in 10 years?	5500	0
18.	Speed limit for LV along this section (mph)?	65	0
19.	Speed limit for SU and CV along this section (mph)?	55	65
20.	Current LV percentage of total ADT?	69.6%	0.0%
21.	Future LV percentage of ADT in 10 years?	63.0%	0.0%
22.	Current SU percentage of total ADT?	23.8%	0.0%
23.	Future SU percentage of ADT in 10 years?	29.8%	0.0%
24.	Current CV percentage of total ADT?	6.6%	0.0%
25.	Future CV percentage of ADT in 10 years?	7.3%	0.0%

ADT - Average Daily Traffic SU - Single-Unit Vehicle Press Enter
LV - Light Vehicle CV - Combination Vehicle

Other Factors:

26.	Length of the analysis period (number of years)?	20
27.	How many years of this period are construction?	3
28.	Present value discount rate?	10.0%

Press Enter

Facility Construction and 4R Work Cost (in 10^3 dollars):

			Defaults	
29.	Construction cost per lane mile	(unseparated)?	$1,900	$0
30.	Construction cost per interchange	(unseparated)?	$500	$0
31.	Right-of-way acquisition cost/mile	(unseparated)?	$810	$0
32.	Construction cost per lane mile	(w/ barriers)?	$2,660	$0
33.	Construction cost per interchange	(w/ barriers)?	$700	$0
34.	Right-of-way acquisition cost/mile	(w/ barriers)?	$1,134	$0
35.	Average cost per lane mile for major resurfacing?		$108	$0
36.	PSI parameter (delta) (in million 18-kip ESALs)?		2.0	0
37.	PSI parameter (beta) used as the power exponent?		1.2	0
38.	Minimum allowable PSI (lower bound on PSI curve)?		1.5	0
39.	PSI at which resurfacing is desired (0-5 scale)?		2.5	0
40.	Average ESALs per light vehicle?		0.0003	0
41.	Average ESALs per single-unit vehicle?		0.06	0
42.	Average ESALs per combination vehicle?		1.5	0

Press Enter

TABLE 1 (*continued on next page*)

TABLE 1 (*continued*)

Value-of-Time and Accident Costs (in dollars):

	Defaults	
43. Light vehicle value-of-time per hour?	$5.00	$0.00
44. Single-unit vehicle value-of-time per hour?	$10.00	$0.00
45. Combination vehicle value-of-time per hour?	$15.00	$0.00
46. Light vehicle accident rate per LV MVM?	0.986	0.000
47. Single-Unit vehicle accident rate per SU MVM?	1.697	0.000
48. Combination vehicle accident rate per CV MVM?	1.555	0.000
49. Accident costs per fatality accident?	$226,800	$0
50. Accident costs per injury accident?	$9,288	$0
51. Accident costs per PDO accident?	$1,242	$0
52. Percent of total accidents blocking no lanes?	59%	0%
53. Percent of total accidents blocking one lane?	28%	0%
54. Percent of total accidents blocking two lanes?	13%	0%
55. Average minutes to clear non-truck involvements?	39	0
56. Average minutes to clear truck involvements?	63	0
57. Maximum queue length before diversion (miles)?	3.0	0.0

Press Enter

pacity on alternate routes in the traffic corridor in specifying future traffic volumes. Ideally, the prediction of travel demand should be brought into equilibrium with the levels of service supplied by all alternate routes in a travel corridor. However, EVFS would need to be integrated with a combined equilibrium assignment and elastic demand model in order to achieve that result. For example, Janson et al. (*4*) developed a network performance evaluation model for evaluating the impacts of adding high-occupancy-vehicle lanes to a transportation corridor that does equilibrate route volumes and travel costs with elastic demand.

The standard FHWA impedance function is used to calculate travel times from traffic volumes. Impedance is a function of a highway section's free-flow travel, which is assumed to equal the section length divided by the speed limit. Impedance is also a function of a section's practical capacity as measured in passenger car equivalents (PCEs) for the various vehicle types. On the basis of the description of the highway section provided by the user, the analysis program computes practical lane capacities for the highway section in the peak and off-peak hours of each year in the planning horizon. These lane capacities are calculated for an assumed lane width of 12 ft and an average vehicle mix. Lane capacities are calculated on the basis of the *1985 Highway Capacity Manual* (*3*). The capacity formula used in EVFS is

$$c = 2{,}000 W T_{SU} T_{CV} \quad (1)$$

where

c = lane capacity (in vehicles per lane-hour),
W = lane width and clearance adjustment factor,
T_{SU} = truck adjustment factor for SU vehicles, and
T_{CV} = truck adjustment factor for combination vehicles.

$$T_{SU} = 100/[100 + (E_{SU} - 1)P_{SU}]$$

$$T_{CV} = 100/[100 + (E_{CV} - 1)P_{CV}]$$

where

E_{SU} = PCE for SU vehicles,
E_{CV} = PCE for combination vehicles,
P_{SU} = percentage of SU vehicles in traffic flow, and
P_{CV} = percentage of combination vehicles in traffic flow.

The PCE values presented in Table 2 are used in the calculation of lane capacities according to the vehicle mix percentages and traffic volumes specified by the user. This set of passenger car equivalents was recommended for urban freeways by FHWA (*5*). EVFS computes the total volume of passenger car equivalents on the highway section based on the average percentages of single-unit and combination vehicles specified by the user. The PCE values are adjusted for hourly peak and off-peak traffic volumes in each year of the analysis period. The PCE values in Table 2 are also adjusted for the average gradient of the highway section based on the *1985 Highway Capacity Manual* (*3*).

For cases being analyzed in which there are both LV and MV lanes, the LV volume in the MV lanes is estimated by equating the volume-to-capacity (v/c) ratios of the LV and MV lanes. This estimate assumes that LV travelers will choose between the LV and MV lanes so as to satisfy the user equilibrium principle of equal travel times for LV travelers in both sets of lanes. This assumption of equal LV travel times does not account for other factors that may cause a different proportion of LV travelers to use the MV lanes, such as the perceived risk of traveling with heavy vehicles, and the uncertainty of egress options from both the LV and MV lanes. However, equating the LV travel times (or v/c ratios) does allow the PCE values used in calculating the practical capacity

TABLE 2 PASSENGER CAR EQUIVALENTS FOR URBAN FREEWAYS

Vehicles per Lane-Hour	Light Vehicles	Single-Unit Vehicles	Combination Vehicles
0-599	1.0	1.1	1.1
599-999	1.0	1.2	1.2
1000-1499	1.0	1.3	1.4
1500-1799	1.0	1.4	1.8
1800+	1.0	1.6	2.0

Source: Sequin et al. (1982). These values assume an average grade of less than 4% for single-unit vehicles, and less than 2% for combination vehicles.

of each set of lanes to depend on traffic volume, vehicle mix, and road gradient. The equation is as follows:

$$V_{LVLV}/C_{LV} = (V_{LVMV} + V_{SUMV} + V_{CVMV})/C_{MV} \tag{2}$$

where

V_{LVLV} = LV volume per lane-hour in the LV lanes,
V_{LVMV} = LV volume per lane-hour in the MV lanes,
V_{SUMV} = SU volume per lane-hour in the MV lanes,
V_{CVMV} = CV volume per lane-hour in the MV lanes,
C_{LV} = vehicle capacity per lane-hour of LV lanes, and
C_{MV} = vehicle capacity per lane-hour of MV lanes.

Both V_{LVLV} and C_{LV} can be computed without any adjustments for the PCEs of other vehicles. However, the split of light vehicles between the LV and MV lanes between depends on the volume of trucks in the mixed-vehicle lanes. This means that the PCE values and vehicle mix percentages used to compute c_{MV} must be brought into balance with the volume of light vehicles in the mixed-vehicle lanes. Because of the rather large volume increments given by Table 2, the balance of light vehicles to use the MV lanes can be found within a few iterations of calculations and comparisons.

Vehicle travel times by vehicle and lane type are used to calculate the total value-of-time difference between cases of with and without the exclusive vehicle lanes, and these travel times are converted to speeds for running cost calculations. The running costs of light vehicles, SU trucks, and combination vehicles for different road grades and curves were obtained from AASHTO (*2*). These running costs are updated to 1985 dollars on the basis of the CPI, and are multiplied by the volumes of light, SU, and combination vehicles in each year of the analysis period. The value of time and running cost totals computed for each year are discounted and summed to 1985 present values on the basis of the specified discount rate.

Traffic flow conditions and travel speeds depend on the average mix of vehicles on a highway section. Vehicle mix percentages computed from statistics in which all counted vehicles do not travel the same distance must be computed on the basis of VMT. Accident rates and severities depend on the vehicle mix, and the total value of time computed for all vehicles must also account for the VMT mix of freight and passenger vehicles. The frequency of resurfacing, as affected by cumulative axle loadings, also depends on the vehicle mix. Default values of VMT mix obtained from FHWA (*6*) are presented in Table 3.

Values of time used as defaults in EVFS were used in a 1979 application of the FHWA Highway Investment Analysis Package (*7*). These values are $3.20, $7.00, and $10.00 per hour for light vehicles, SU vehicles, and combination vehicles, respectively. Adjusting for price changes from 1979 to 1985 with a CPI of 1.482 increases these default values to roughly $5, $10, and $15, respectively. The default value of time for light vehicles assumes an average occupancy of roughly 1.3 persons per vehicle. Because buses are included with light vehicles, the average occupancy may be higher for highways serving several bus routes that have a significant number of buses in the traffic stream. Highways leading to central business districts and large employment centers can also attract more car and van pools. Accounting for these factors, the user of EVFS must enter a value of time for light vehicles

TABLE 3 AVERAGE VMT MIX PERCENTAGES ON INTERSTATE HIGHWAYS

Area Type	Light Vehicles	Single-Unit Vehicles	Combination Vehicles
Rural	64.2%	28.6%	7.2%
Suburban	69.6%	23.8%	6.6%
Urban	75.0%	19.0%	6.0%

Source: Rural and urban values from FHWA (1988). Suburban values were computed here as the averages of the rural and urban values.

that corresponds to the average occupancy observed for a particular highway section.

CONSTRUCTION AND RESURFACING COSTS

Although benefits do not begin to accrue until after construction, all future benefits and costs are discounted to time 0 (i.e., the beginning of the first year), and all benefits and costs are calculated in 1985 dollars. With the assumption that inflation affects all goods at the same rate, discounted costs and benefits generated by EVFS can be inflated or deflated to an alternate year on the basis of the CPI without affecting the benefit-cost ratio of each alternative. The present value discount rate is assumed to be 10 percent according to Federal Circular 76 published by the U.S. Office of Management and Budget. Sensitivity of public investment analyses to the discount rate are usually performed with values of 8 and 12 percent.

Construction and right-of-way acquisition costs presented in Table 4 were obtained from the *1985 Characteristics of Urban Transportation Systems* (also referred to as the "CUTS manual"). Construction costs per lane-mile as given by the CUTS manual assume that average percentages of the highway section are elevated, at-grade, or depressed for rural, suburban, and urban areas, although these percentages are not documented in the CUTS manual.

The frequency and cost of 4R work (reconstruction, rehabilitation, resurfacing, or restoration) is affected by many site-specific factors such as roadway design, climate, soils, subbase, and axle loadings. Although highway pavements are usually designed to provide 20 years of service before reconstruction is required, greater than expected heavy-vehicle volumes can often make earlier 4R work necessary. When 4R work is needed, a trade-off exists between longer-lasting, more-costly remedial actions and less-durable, lower-cost actions. In EVFS, the estimation of 4R work costs over the analysis period is limited to periodic asphalt resurfacings. Some type of 4R work is required at various times of a road's life to maintain its pavement serviceability index (PSI) above a minimum acceptable level. The PSI gauges the functional performance of a road's pavement as it affects quality of ride and safety to the traveling public. The PSI is a weighted composite index of pavement distress observations collected by mechanical, visual, and photographic means.

The PSI of heavily traveled roads depends most significantly on the accumulation of equivalent single-axle loadings (ESALs) since it was last resurfaced. As such, the PSI is usually modeled as a function of ESALs, with an adjustment factor to normalize for road differences by functional class, pavement type, and location. The rate of PSI deterioration also depends on a road's age since last reconstruction caused by changes in the structural integrity of the underlying layers, but this effect is not considered in EVFS. Research performed at the Texas Transportation Institute (TTI) found that a modified version of the original AASHTO Road Test equation was superior for predicting PSI deterioration over time and generally had superior properties (*9*). Most notably, the TTI equation asymptotically approaches a minimum pavement condition, as pavement sections are observed to do, rather than degrade into negative values as the AASHTO equation does. The TTI equation defined as follows is an *S*-shaped function that ranges between 0 and 5:

$$\mathrm{PSI} = P_i - (P_i - P_f)\exp[-(\sigma/Q)^{\beta}] \qquad (3)$$

where

P_i = initial PSI of the pavement;
P_f = minimum acceptable PSI of the pavement;
Q = quantity of normalized load to pavement surface, usually expressed in millions of 18-kip ESALs;
σ = quantity of normalized load to pavement surface that reduces PSI from P_i to P_f; and
β = parameter affecting the *S*-shape of the PSI curve.

In the TTI equation, σ is a quantity of normalized load that is used to fit the equation, but σ does not equal the amount of load that reduces the PSI from PSI_i to PSI_f because it is

TABLE 4 CONSTRUCTION COSTS PER LANE-MILE FOR FREEWAY IMPROVEMENTS

	Rural	Suburban	Urban
New 4 Lane Freeway	1.11	1.49	1.88
New 6 Lane Freeway	1.22	1.73	2.24
Major Widening	1.50	1.90	2.30
Right-of-Way Costs	0.39	0.41	0.42
Cost per Interchange	0.40	0.50	0.60

Note: All values are in millions of 1983 dollars, which are multiplied by 1.08 for the 1983-1985 CPI change.

Source: Rural and urban values from UMTA (1985). Suburban values were computed here as averages of rural and urban values. Right-of-way costs are assumed equal to the cost difference per lane mile of new 4 lane freeway construction and major widening. Cost per interchange estimated from Roy Jorgensen (1975).

part of the exponential term. The TTI equation has been fit fairly closely to observed data using nonlinear regression to estimate the best fitting values of σ and β. A user of EVFS may alter any of the three parameters (σ, β, or P_f) that affect the shape of the PSI curve used to predict the frequency of pavement resurfacing.

Figure 1 shows a family of three TTI curves for asphalt overlays with σ and β equal to 2.0 and 1.2, respectively. These parameters were then estimated by Garcia-Diaz and Riggins (*9*) on the basis of 77 sample asphalt overlay sections. These three curves are for newly resurfaced roads with three different average annual loadings of 500,000, 700,000, and 900,000 ESALs. In each case, the pavement deteriorates to a PSI of 2.5 when the cumulative ESALs exceed 5 million. The average ESAL loading per vehicle of each type was estimated on the basis of values given by the Asphalt Institute (*10*) and Wright and Paquette (*11*) for concrete pavements. In EVFS, the default values of ESALs per vehicle that the user may override are 0.0003 ESALs per light vehicle, 0.06 ESALs per SU vehicle, and 1.5 ESALs per combination vehicle.

Uzarski and Darter (*12*) report average resurfacing costs (in 1983 dollars) for different road classes and PSI values when the overlay is performed. These costs were estimated for Interstates and urban freeways in ongoing research on the PAVER pavement management system. These costs are presented in Table 5 for PSI values between 1.0 and 4.0 for primary highways. These values exhibit an average resurfacing cost of

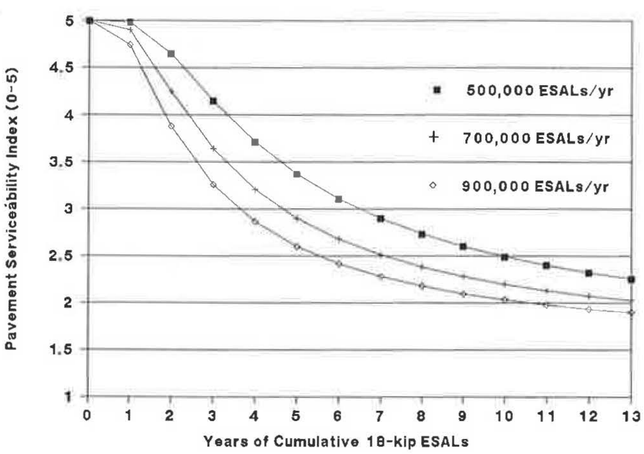

FIGURE 1 Pavement serviceability index for asphalt overlays.

about $100,000 (in 1983 dollars) per lane-mile of 6-in. overlay to a highway with a 2.5 PSI, which generally agrees with other data sources, including the 1985 CUTS manual (*8*).

A default resurfacing cost of $108,000 (including an adjustment of 1.08 for the 1983 to 1985 CPI change) per lane-mile of highway with a PSI of 2.5 is used by EVFS to calculate resurfacing costs. This cost is adjusted for PSI values other than 2.5 in scale proportion to the costs exhibited in the 6-in. overlay column. The following example explains how EVFS estimates resurfacing costs for all lanes over the analysis period. An Interstate lane with an ADT of 20,000 distributed as 72 percent light vehicles, 20 percent SU vehicles and 8 percent combination vehicles will experience roughly 730,000 18-kip ESALs per year. At that loading rate, and the policy to resurface when the PSI reaches 2.5, the road will need to be resurfaced every 7 years, assuming no growth in traffic or change in the vehicle mix during that time.

After 20 to 30 years, most urban Interstates require extensive rehabilitation and reconstruction. In EVFS, it is assumed that all existing lanes will be resurfaced at the time that new lanes are added (i.e., all lanes begin the analysis period with a PSI of 5.0), and that the analysis period terminates before the next major reconstruction. This assumption can be removed by adding an average cost per lane-mile of reconstruction into the average resurfacing cost. The resurfacing frequency for non-barrier-separated lanes depends on which set of lanes requires it first, and all lanes are assumed to be resurfaced at that time. EVFS determines the frequency of resurfacing separately for each set of barrier-separated lanes, because the timing of resurfacing may vary between these sets of lanes depending on the ESALs. The cost of routine maintenance is not included by EVFS, because these activities will generally be the same regardless of lane use policies.

CALCULATIONS OF TOTAL ACCIDENT COSTS

Average accident rates are assumed to include the three standard accident categories: fatal, injury, and property damage only (PDO). Unfortunately, most compilations of accident data do not disaggregate the data by vehicle involvement type in the way that is needed to estimate the effects of separating light and heavy vehicles. For example, a recent study on twin-trailer trucks by TRB (*13*) reported fatal and injury accident rates for single-trailer and multitrailer trucks, but their rates

TABLE 5 RESURFACING COSTS PER LANE-MILE OF FREEWAY BY PSI

PSI	2" overlay	4" overlay	6" overlay
4.0	26822	53574	80397
3.5	27526	54278	81101
3.0	28934	55686	82509
2.5	46746	73427	100320
2.0	63782	90534	117357
1.5	75258	102010	128832
1.0	86662	113414	140237

Note: All values are in 1983 dollars, which are multiplied by 1.08 for the 1983-1985 CPI change.

of involvement with other vehicle types were not indicated. Studies that do distinguish between accidents involving light, SU, and combination vehicles (or similar categories) generally do not report the complete cross tabulation of that data.

The following relationship was developed for EVFS to predict the effects of separating light and heavy vehicles. The total number of accidents of all types equals the sum of nine terms representing single- and multiple-vehicle accidents within and between vehicle types according to the following equation.

$$\mathrm{ACC} = V_{LV}R_{LV1} + V_{LV}R_{LV2} + V_{SU}R_{SU1} + V_{SU}R_{SU2} + V_{CV}R_{CV1} + V_{CV}R_{CV2} + \frac{V_{LV}R_{LV3}V_{SU}R_{SU3}}{(V_{LV} + V_{SU})R_{LVSU}} + \frac{V_{LV}R_{LV4}V_{CV}R_{CV3}}{(V_{LV} + V_{CV})R_{LVCV}} + \frac{V_{SU}R_{SU4}V_{CV}R_{CV4}}{(V_{SU} + V_{CV})R_{SUCV}} \tag{4}$$

where

- ACC = total number of accidents of all types,
- V_{LV} = total light-vehicle million vehicle-miles (MVM),
- V_{SU} = SU vehicle MVM,
- V_{CV} = combination vehicle MVM,
- R_{LV1} = single LV accident rate per LV MVM (0.199),
- R_{LV2} = multiple LV accident rate per LV MVM (0.671),
- R_{LV3} = LV with SU accident rate per LV MVM (0.020),
- R_{LV4} = LV with CV accident rate per LV MVM (0.069),
- R_{SU1} = single SU accident rate per SU MVM (0.061),
- R_{SU2} = multiple SU accident rate per SU MVM (0.019),
- R_{SU3} = SU with LV accident rate per SU MVM (0.566),
- R_{SU4} = SU with CV accident rate per SU MVM (0.044),
- R_{CV1} = single CV accident rate per CV MVM (0.099),
- R_{CV2} = multiple CV accident rate per CV MVM (0.035),
- R_{CV3} = CV with LV accident rate per CV MVM (0.849),
- R_{CV4} = CV with SU accident rate per CV MVM (0.019),
- R_{LVSU} = LV with SU accident rate per (LV + SU) MVM (0.019),
- R_{LVCV} = LV with CV accident rate per (LV + CV) MVM (0.064), and
- R_{SUCV} = SU with CV accident rate per (SU + CV) MVM (0.013).

A study by Goodell-Grivas (*14*) for FHWA reports accidents for these nine different types of vehicle interactions, and that data was converted into rates per MVM by vehicle type. These rates are shown in parentheses in the preceding list, and they result in a total accident rate of 0.876 per MVM of all vehicle types.

Implicit in the preceding equation is that all VMT values are generated on a given highway section within a certain time period. Hence, for a given highway section, more accidents are predicted to occur when greater traffic volumes or greater speeds generate greater VMT within a given period of time. The data in the Goodell-Grivas study (*14*) represented a relatively small sample along a specific section of freeway, so rates calculated from those data may not be generally applicable to other highway sections. Additional studies are needed to determine the transferability of accident rates in an equation of this form to predict accidents on other highway sections. A few recent studies, including Alassar (*15*) and Khasnabis and Al-Assar (*16*), have fitted alternative functional relationships to accident rates and traffic densities of different vehicle types on major highways.

Accident rates vary widely by the type of highway surroundings, and also by the study in which they are found. For example, accident rates from two different sources are presented in Table 6. Rates from Pigman et al. (*17*) are exhibited for Interstate sections with and without bridges and interchanges. Some of the variation between these rates is because of the classification of sample highway sections as freeways, expressways, or Interstates, and the criteria by which they were defined to be rural, suburban, or urban. Other differences in highway sections that affect accident rates are curvature, grade, vehicle mix, numbers of lanes, interchanges, bridges, and tunnels.

Meyers (*18*) compiled the accident data presented in Table 7 for controlled-access expressways for these three vehicle types and sorted by whether the accident caused fatalities, injuries, or property damage only. By comparison, a recent article by Giuliano (*19*) examining accidents on the I-10 freeway in Los Angeles, California, showed that 63 percent of all accidents involve no injuries, which agrees closely with the value of 67 percent computed on the basis of Meyers' (*18*) data. Among injury-causing accidents examined by Giuliano (*19*), 66 percent caused injuries to one person, 22 percent caused injuries to two persons, and 12 percent caused injuries to three or more persons. Average numbers of fatalities and

TABLE 6 TOTAL ACCIDENT RATES ON CONTROLLED-ACCESS HIGHWAY SECTIONS

Area Type	AASHTO (1977)	Pigman (1981)[a]	Pigman (1981)[b]
Rural	0.79	0.57	0.49
Suburban	1.07	0.77	0.61
Urban	1.43	3.05	2.07
Total	1.23	1.22	0.90

Note: Accident rates are per million vehicle miles, and include all accidents causing fatalities, injuries, and property damage only.

a) rates are with bridges and interchanges.

b) rates are without bridges and interchanges.

Sources: Shown by column headings.

TABLE 7 ACCIDENT RATES BY VEHICLE TYPE ON CONTROLLED-ACCESS EXPRESSWAYS

	Accident Type			
Vehicle Type	Fatal	Injury	PDO	Total
Passenger	0.013	0.373	0.748	1.134
Single-Unit	0.032	0.579	1.340	1.951
Combination	0.028	0.510	1.249	1.787

Note: Accident rates are per million vehicle miles, and include all accidents causing fatalities, injuries, and property damage only.

Source: Meyers (1981).

injuries per accident have already been factored into the costs presented in Table 8 by their sources such that these costs are given per accident.

EVFS applies the AASHTO (*2*) accident rates by area type and Meyers' (*18*) total accident rates by vehicle type to generate default values to Questions 46 to 48 that the user may override. Meyers' (*18*) accident rates, which are assumed to represent suburban highways, are multiplied by 0.79/1.07 for rural highways, and by 1.43/1.07 for urban highways. The Goodell-Grivas (*14*) rates listed earlier are then used to disaggregate the accident rates by vehicle involvement type. Other studies of accident rates may provide the analyst with alternative rates to be substituted as nonzero values for the default rates. In either case, the default rates, or their substitutes, are proportioned to accident types according to Table 7, and these rates are proportioned to the nine vehicle involvement types according to the values listed earlier from the Goodell-Grivas (*14*) study.

Average accident costs for each accident type (fatal, injury, and property damage only) are presented in Table 8 from a variety of sources such as NHTSA (*20*), the National Safety Council (NSC) (*21,22*), and the Highway Investment Analysis Package (HIAP) (*7*). Some of these accident costs are summarized by Fleischer (*23*). These valuations can vary widely depending on their source and application.

EVFS calculates total accident costs per MVM for mixed and exclusive vehicle lanes as follows. The 1985 NSC accident costs are multiplied by the accident rates per MVM just described by area, accident, and vehicle involvement type. The total accident cost of light-vehicle lanes equals the LV-only accident rate per LV MVM times the average LV accident cost. The total accident cost of mixed-vehicle lanes equals the sum of the products of the accident rates per MVM for the different vehicle involvement types times their respective average accident costs. The total accident cost for each heavy-vehicle lane is computed similarly to mixed-vehicle lanes except that only SU and combination vehicles are taken into account.

CALCULATIONS OF ACCIDENT QUEUING DELAYS

EVFS uses a deterministic queuing model to estimate the total delay caused by accidents predicted to occur on both mixed and exclusive vehicle facilities. Morales (*24*) found this type of queuing model to yield close estimates of accident delays on freeways in a study for FHWA. The total delay caused by an accident depends heavily on traffic volumes at the time of an accident, the number of blocked and unblocked lanes, the duration of lane blockage, and the number of route diversion options available to vehicles upstream from the accident scene. The study by Goodell-Grivas (*14*) concluded that travel time delays on urban freeways caused by truck accidents can cost more than twice the total fatality, injury, and property damage cost of those accidents.

An accident causes queuing and vehicle delays because the vehicle arrival rate (hourly vehicle volume) exceeds the vehicle service rate (unblocked lane capacity) during the accident clearing and queue dissipation stages of an incident. The accident-clearing stage is the time at which an accident first occurs to the time at which all accident wreckage and emergency equipment are cleared from blocking any lanes. The queue dissipation stage is the time at which the accident is cleared from blocking any lanes to the time at which the residual traffic queue disappears and normal freeway operations are restored. Figure 2 shows a graph of the queuing delays caused by a lane blocking accident as estimated by the deterministic queuing model.

The total delay time caused by an accident equals the shaded area shown in Figure 2. Lines *A* and *B* have slopes equal to the vehicle service rates of a highway during the accident clearing and queue dissipation stages, respectively. The accident clearing stage is from the time t_0 when the accident occurs (assumed to be time 0) to the time t_2 when all lanes are cleared. The queue dissipation stage is from the time t_2 to the time t_3 when the queue disappears. At time t_2, when

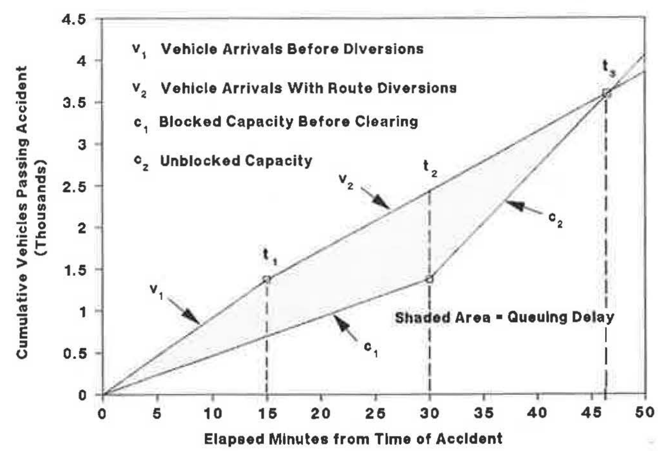

FIGURE 2 Deterministic queuing model of accident delays.

TABLE 8 ACCIDENT COSTS BY ACCIDENT TYPE

	Accident Costs				
	NHTSA (1975$)	NSC (1976$)	HIAP (1979$)	NSC (1983$)	NSC (1985$)
Fatal	287,175	125,000	122,000	210,000	226,800
Injury	3,185	4,700	7,550	8,600	9,288
PDO	520	670	600	1,150	1,242

Sources: Shown by column headings; 1985 NSC costs equal 1983 NSC costs updated to 1985 dollars with a CPI factor of 1.08.

the accident is cleared from blocking any lanes, the service rate returns to its preaccident level (denoted as C_2), which exceeds the current arrival rate, and the queue begins to dissipate. Morales (*24*) found that a highway may not return to its preaccident service rate at one time, and that short intermediate steps or piecewise linear segments between lines *A* and *B* can be used to represent certain accident clearing processes in more detail. However, most of the accidents reported by Morales (*24*) do not require this additional detail, and this additional detail altered the total delay by less than 10 percent in cases where it was used.

The vehicle service rate of unblocked lanes during the accident clearing stage (denoted as C_1) depends on the number of open lanes, plus other factors that affect vehicle flow such as smoke, debris, visible wreckage, and emergency equipment. This lower vehicle service rate can be estimated by adjusting the capacity of open lanes for the merging and caution exhibited by vehicles in passing an accident. The accident data reported by Goodell-Grivas (*14*) indicate that the open lanes beside accidents to have an average service rate of 80 percent of their usual capacity. For example, if only two of four lanes remain open (where the usual capacity of each lane is 2,000 veh/hr), the vehicle service rate of the open lanes will, on average, reduce to 3,200 veh/hr because of the effects of driving behavior near an accident scene.

With regard to vehicle arrival rates, the queuing model used in EVFS allows the arrival rate of vehicles at the rear of the queue to decrease at time t_1 during the accident clearing stage because of excessive queue length, route diversion options, and advanced warnings. In Figure 2, lines *C* and *D* have slopes equal to the vehicle arrival rates from time t_0 to time t_1 and from time t_1 to time t_3, respectively. The time t_1 at which the arrival rate decreases depends on how quickly the queue lengthens to the point at which drivers consider the route diversion options available to them. The EVFS assumes that the arrival rate will decrease when the queue length equals one-half the average distance between interchanges on the highway section being evaluated. The basis for this assumption is that the nearest upstream interchange at which drivers can divert to other routes will, on average, be one-half the average distance between interchanges if accidents are randomly distributed between interchanges.

Although travel time impacts on alternate routes are not estimated by EVFS, the extent of route diversion, which depends on the availability and reliability of alternate routes, affects the vehicle arrival rate into the queue. The arrival rate is expected to decrease prior to or at time t_2, because the queue begins to shorten after then. A reasonable assumption supported by data in Goodell-Grivas (*14*) is that the initial vehicle arrival rate V_1 will not decrease to a rate V_2 below the service rate C_1 of the unblocked lanes. The accident data reported by Goodell-Grivas (*14*) indicate an average reduction in the arrival rate at time t_1 equal to 33 percent of the difference between V_1 and C_1. This route diversion percentage will be greater on barrier-separated facilities where vehicles can divert to alternate lanes that are clear of the accident, but not exit the highway entirely.

Computationally, the total travel time delay of an accident is equal to the shaded area in Figure 2 as given by the following equation.

$$\begin{aligned}\text{Delay} = {} & 0.5[t_1^2(V_1 - C_1) - (t_2 - t_1)^2(C_2 - C_1)] \\ & + 0.5(t_3 - t_1)[t_1(V_1 - C_1) + (t_2 - t_1)(C_2 - C_1)]\end{aligned} \quad (5)$$

where

Delay = total vehicle queuing delay (hours—not weighted by vehicle differences in value of time or occupancy);

N_l = number of highway section lanes (blocked or unblocked);

L_q = length of queue (in miles) at which vehicle arrival rate decreases, assumed equal to one-half the average distance between interchanges unless analyst inputs a different value;

t_1 = minimum $[t_2, (105.6\ N_lL_q)/(V_1 - C_1)]$ = hours after accident when vehicle arrival rate changes caused by queue length, diversion options, and advanced warnings—assumed to occur at t_1 or when the queue in all lanes N_l reaches length L_q, allowing 50 ft per vehicle in slow traffic;

t_2 = hours after accident when all lanes are cleared (input);

t_3 = $t_1 + [t_1(V_1 - C_1) + (t_2 - t_1)(C_2 - C_1)]/(C_2 - V_2)$ = hours after accident when queue disappears (calculated);

V_1 = vehicle arrival rate per hour until time t_1—assumed equal to the hourly vehicle volume at the time of the accident;

V_2 = vehicle arrival rate per hour from time t_1 to time t_3—assumed equal to $V_1 - 0.35(V_1 - C_1)$ for unseparated facilities, and equal to $V_1 - 0.70(V_1 - C_1)$ for barrier-separated facilities;

C_1 = vehicle service rate per hour until t_2 when all lanes are cleared—assumed to equal 80 percent of the unblocked lane capacity weighted by PCEs for vehicle mix and volume; and

C_2 = vehicle service rate per hour after t_2 when all lanes are cleared—assumed to equal the total lane capacity weighted by PCEs for vehicle mix and volume.

EVFS accounts for percentages of accidents that cause zero, one, or two lanes to be closed. A recent analysis of accidents on the I-10 Freeway in Los Angeles by Giuliano (*19*) indicated that 59 percent caused no lane closures, 28 percent caused one lane to be closed, and 13 percent caused two or more lanes to be closed. Although truck involvement also affects the severity of lane blockage, specific data on that relationship could not be found. An analysis of variance performed by Giuliano (*19*) did indicate that incident duration was significantly affected by truck involvement. The average incident duration of accidents involving trucks was 63 min, versus only 39 min for nontruck involvements. The incident duration variance for accidents involving trucks was also much greater than that for nontruck involvements. Incident duration was defined in the study as the time at which an accident is first reported to the time at which the accident is reported to be cleared. Incident duration by this definition does not include the queue dissipation time from t_2 to t_3 when normal traffic resumes.

Because most of the cases being analyzed with EVFS will involve mixes of lane types, certain lane use assumptions must be made to estimate the vehicle mix, volume, and queuing delay in the unblocked lanes because of a lane-blocking accident. The number of vehicles diverted into unblocked lanes depends on whether the two types of lanes are barrier separated, and also on the use of changeable message signs to direct lane use. If the two lane types are not barrier separated, then the assumption is made that all vehicle types will use the unblocked lanes to maneuver around the accident. However, if the two lane types are barrier separated, then it depends a great deal on how changeable message signs are used to divert traffic.

Total delay time is composed of delays both for light and for heavy vehicles, so vehicle mix is used to calculate a weighted value of delay time. The queuing calculations of travel time delay are only applied to lanes on the accident side of barrier-separated lanes, and no travel time adjustments are made for increased traffic on the other side of the barrier, because those impacts are assumed to be negligible. In all cases (both barrier-separated and unseparated), the vehicle mix in the lanes with an accident is held equal to the vehicle mix under normal operating conditions, despite diversions of some vehicles to other lanes or routes.

Accident rates may also vary by time of day because of traffic densities, speeds, and visibility conditions. Because data on this relationship for urban freeways were not available, EVFS assumes the same accident rates per MVM both for peak and for off-peak hours. As such, greater number of accidents per hour are predicted to occur during peak periods because of greater VMT per hour. EVFS does compute the number of accidents and queuing delays separately for both the peak and off-peak periods, and operating costs for vehicles caught in accident queues are adjusted for slower speeds. Last, clean-up and reporting costs are estimated to be $1,000, $5,000, and $10,000 per accident for light, SU, and combination vehicle accidents, respectively.

EXAMPLE APPLICATION OF EVFS

This section presents an example analysis of five alternative facility designs for a 30-mi highway section that currently has three mixed-vehicle lanes in each direction. The development of this example is based on the recent widening of US-59 that runs southwest from Houston to Richmond, Texas. This freeway is a major commuting artery feeding downtown Houston, and also a major truck route to and around Houston. The highway passes both through densely developed and less-constructed areas, so its location has been designated as suburban in the following analysis. Starting in 1987, parts of this highway section were widened from 3 to 5 MV lanes in each direction. In addition, a two-lane transitway was constructed in the median area of the highway that will carry buses, vanpools, and carpools. Traffic volumes on this highway section averaged about 80,000 vehicles per day in each direction in 1987, projected to increase to 110,000 vehicles per day in each direction in 10 years.

In addition to Case 0 (the base or do-nothing case), the four exclusive vehicle facilities considered in this example are as follows:

- Case 1: Designate one of three existing lanes for light vehicles only.
- Case 2: Widen from three to five MV lanes.
- Case 3: Widen from three MV lanes to two LV and three MV lanes.
- Case 4: Same as Case 3, except with LV and MV lanes barrier-separated.

Table 9 presents the general site information and traffic characteristics input to this EVFS example. The site information is exhibited for Case 4. The only differences in site information between cases are the number of future lanes of each type, number of new lanes of right-of-way to acquire, and whether or not the different lane types are barrier separated (Questions 3 to 7). Values for the current ADT and the annual increase in ADT were input to agree with the estimates just described, and the AASHTO division of ADT between peak and off-peak periods was accepted. The only change made to the default traffic characteristics was to increase the speed limit from 55 to 65 mph. All other factors including construction costs, values of time, and accident costs are the default values presented earlier in Table 1. The planning horizon was set to 20 years, with project completion after 3 years, and a discount rate of 10 percent.

Table 10 presents the EVFS results for the base case (Case 0) and the four alternative cases (Cases 1 to 4). Net benefits and net costs reported for Cases 1 to 4 are differences in benefits and costs from Case 0. Thus, for comparison purposes, net benefits and net costs equal zero for Case 0, and neither the net present value nor the benefit-cost ratio of Case 0 is relevant. Costs, benefits, and other performance measures are presented in more detail for each alternative case in Table 11, where vehicle operation costs are shown to be the most significant cost factor.

Table 10 presents the benefit-cost ratios and net present values of each facility alternative both with and without vehicle operating costs. Because of their many values, vehicle operating costs are the only costs read by EVFS from data files that cannot be modified by the spreadsheet user interface. A forthcoming revision of the AASHTO Red Book (*2*) will provide updated operating costs that revise these data files. The net present value of Case 1 is the same both with and without vehicle operating costs because traffic is predicted to operate at roughly the same speed in either case. Thus, without expanding the highway, travel times and costs will remain at high levels. The main benefit of Case 1 is lower accident costs because of vehicle separation.

The benefit-cost ratios of Cases 2 to 4 are only slightly greater than one when vehicle operating costs are included, but they are much greater than one without vehicle operating costs. The widening of this congested highway allows vehicles to travel at faster speeds, which results in greater vehicle operating costs per mile for both light and heavy vehicles. Both light and heavy vehicles achieve their lowest operating costs at speeds between 45 and 50 mph according to the AASHTO Red Book (*2*). Compared to Case 1, Cases 2 to 4

TABLE 9 SITE AND TRAFFIC CHARACTERISTICS INPUT TO EVFS (EXAMPLE)

General Site Information:

1.	Is this a rural, suburban, or urban highway section R/S/U?	S
2.	Current mixed-vehicle lanes in each direction (0-6)?	3
3.	Future mixed-vehicle lanes in each direction (0-6)?	3
4.	Future light-vehicle lanes in each direction (0-6)?	2
5.	Future heavy-vehicle lanes in each direction (0-4)?	0
6.	Number of new lanes of right-of-way to acquire (0-4)?	2
7.	Will exclusive vehicle lanes be barrier separated (Y/N)?	Y
8.	Length of section in miles (including decimal places)?	30.0
9.	Number of interchanges along this section?	5
10.	Average road gradient along section (typical value = 0%)?	0%
11.	Average curvature along section (typical value = 2 deg.)?	2

Traffic Characteristics:

		Defaults	
12.	Current average daily traffic (ADT) (one direction)?		80000
13.	Average annual increase in ADT (one direction)?		3000
14.	Current peak-period volume/hr (3 hours/day)?	6667	0
15.	Future peak-period volume/hr in 10 years?	9167	0
16.	Current off-peak volume/hr (15 hours/day)?	4000	0
17.	Future off-peak volume/hr in 10 years?	5500	0
18.	Speed limit for LV along this section (mph)?	65	0
19.	Speed limit for SU and CV along this section (mph)?	55	65
20.	Current LV percentage of total ADT?	69.6%	0.0%
21.	Future LV percentage of ADT in 10 years?	62.3%	0.0%
22.	Current SU percentage of total ADT?	23.8%	0.0%
23.	Future SU percentage of ADT in 10 years?	29.8%	0.0%
24.	Current CV percentage of total ADT?	6.0%	0.0%
25.	Future CV percentage of ADT in 10 years?	7.3%	0.0%

LV = Light Vehicle SU = Single-Unit Vehicle CV = Combination Vehicle

TABLE 10 SUMMARY OF THE EVFS EXAMPLE RESULTS

Results with vehicle operating costs

	Benefits	Costs
Case 0	1796154	2390025

	Net Benefits	Net Costs	Net Present Value	B/C Ratio
Case 1	64336	27156	37180	2.369
Case 2	518993	398391	120602	1.303
Case 3	551301	457605	93696	1.205
Case 4	552238	470031	82207	1.175

Results without vehicle operating costs

	Benefits	Costs
Case 0	1796154	68529

	Net Benefits	Net Costs	Net Present Value	B/C Ratio
Case 1	64336	27156	37180	2.369
Case 2	518993	139595	379398	3.718
Case 3	551301	198809	352491	2.773
Case 4	552238	211235	341003	2.614

Note: All values are shown in 1000's of dollars.
Costs include vehicle operating costs.

TABLE 11 DETAILED RESULTS FOR THE EVFS EXAMPLE

COST SUMMARY (in $1000s)	Base Case	Case 1	Net	Case 2	Net
Resurfacing Lanes	$68529	$95685	$27156	$54894	-$13635
Vehicle Operation	$2321496	$2321496	-$0	$2580292	$258796
New Construction	$0	$0	$0	$104630	$104630
Right Of Way	$0	$0	$0	$48600	$48600
Total	$2390025	$2417181	$27156	$2788416	$398391

BENEFIT SUMMARY (in $1000s)	Base Case	Case 1	Net	Case 2	Net
Travel Time	$1345819	$1345820	-$1	$1089779	$256040
Accident Costs	$172461	$151804	$20657	$172461	$0
Accident Delays	$277874	$234193	$43681	$14921	$262953
Total	$1796154	$1731818	$64336	$1277161	$518993

OTHER PERFORMANCE MEASURES	Base Case	Case 1	Net	Case 2	Net
Total Accidents	44258	38590	-5668	44258	0
Avg. Accident Cost	$10094	$10019	-$75	$10094	$0
Avg. Delay Cost	$22841	$21767	-$1075	$1477	-$21364
Avg. Travel Speed	54.04	54.04	0.00	62.97	8.92

COST SUMMARY (in $1000s)	Base Case	Case 3	Net	Case 4	Net
Resurfacing Lanes	$68529	$114108	$45579	$68465	-$64
Vehicle Operation	$2321496	$2580292	$258796	$2580292	$258796
New Construction	$0	$104630	$104630	$143259	$143259
Right Of Way	$0	$48600	$48600	$68040	$68040
Total	$2390025	$2847630	$457605	$2860056	$470031

BENEFIT SUMMARY (in $1000s)	Base Case	Case 3	Net	Case 4	Net
Travel Time	$1345819	$1089779	$256040	$1089779	$256040
Accident Costs	$172461	$143765	$28696	$143765	$28696
Accident Delays	$277874	$11309	$266565	$10372	$267502
Total	$1796154	$1244853	$551301	$1243916	$552238

OTHER PERFORMANCE MEASURES	Base Case	Case 3	Net	Case 4	Net
Total Accidents	44258	36384	-7873	36384	-7873
Avg. Accident Cost	$10094	$9973	-$121	$9973	-$121
Avg. Delay Cost	$22841	$1340	-$21501	$1205	-$21636
Avg. Travel Speed	54.04	62.97	8.93	62.97	8.93

Note: All costs and benefits are 1985 present value amounts.

have lower benefit-cost ratios but much greater net present values because of the low cost of Case 1. Case 2, which is to widen the highway with additional MV lanes, is the preferred alternative with the highest net present value. Cases 3 and 4 would be more competitive with Case 2 if the cost per accident fatality were increased to $500,000 or higher, or a longer planning horizon were used. Accident costs and delays for Cases 3 and 4 are much lower than for Case 2, but not enough to offset the higher cost of construction.

CONCLUSIONS

EVFS is a useful and flexible model for evaluating the economic feasibility of segregating vehicles on controlled-access highways by designating existing lanes and constructing new lanes to be used exclusively by light or heavy vehicles. EVFS can be used to perform sensitivity analyses of the critical points at which a particular exclusive vehicle facility becomes economically feasible, depending on (a) future traffic volumes on the highway, (b) existing and proposed number of lanes of each type, (c) percentages of heavy and light vehicles in the traffic stream, (d) costs of interchange and lane construction, (e) the pavement resurfacing cost, (f) vehicle operating costs, (g) person and freight values-of-time, and (h) accident rates, costs, and lane closures.

Several test analyses with EVFS similar to the previous example indicated that a few key factors were needed for barrier-separated facilities to be economically feasible. First, peak-hour volumes must exceed 1,800 vehicles per lane-hour, and off-peak volumes must exceed 1,200 vehicles per lane-hour. Second, heavy vehicles must exceed 30 percent of the vehicle mix. Exclusive facilities without barrier separation appear to be warranted for a wider range of traffic volumes and vehicle mixes depending on other site-specific characteristics. On congested highways, particularly during peak travel hours, designating one or two existing lanes exclusively for light vehicles can be a cost-effective traffic management strategy. The example of the previous section indicated this case to have a positive net present value. However, more rapid traffic growth and a longer analysis period will result in the addition of new unseparated lanes for light vehicles to have the greatest net present value.

These estimates of costs and benefits from EVFS should be viewed as midpoints within broad ranges because of the many assumptions needed to simplify numerous site-specific complexities. Relatively small differences between alternative cases of less than 5 percent may not be significant. However, the rankings of alternatives as determined by many test analyses for a given site are likely to be robust. EVFS could be improved by imbedding models for freeway simulation, route assignment, and elastic demand. Such enhancements are needed for improved modeling of route diversion alternatives during traffic accidents, and of traffic attracted from alternate routes because of added capacity. However, this expansion of EVFS would also require much more extensive data preparation on the part of the user. As currently designed, EVFS can be used to generate quick-response evaluations of many alternative facilities in just a few brief sessions.

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