Cost-Benefit Analysis on Deployment of Automated Highway Systems

BIN RAN, KWUN YEE KENNY LEE, AND HAIKUN DONG

The optimal ranges of traffic flow and capacity will be determined for selected scenarios, in which different proportions of automated and conventional traffic will operate simultaneously in an automated highway system (AHS). It is found that there will be a substantial increase in the net benefit and the traffic flow and capacity ranges when there is a higher proportion of AHS traffic. The optimal range of capacity refers to the maximum range of traffic volumes, for which there will be some net benefit, which is the difference between the total cost and the total benefit for each flow. The total cost represents the production and operating costs of the infrastructure and the expenditure borne by the user, whereas the total benefit refers to the time saving to the user. It is concluded that more AHS vehicles should be produced in order to achieve economic efficiency, improved traffic capacity, and safety in travel.

The objective of developing automatic highway systems (AHSs) as part of the Intelligent Transportation System (ITS) is to improve the movement of people and goods in America in the next decades by using advanced technology and communication. AHS is designed to improve traffic capacity and safety and to reduce fuel consumption due to stop-and-go idled delay. The headway between the automated vehicles can be reduced greatly and the fleet can move in platoons with a desirable speed, which will be controlled by the roadside and in-vehicle equipment packages. As a result, the accident rate can be lowered and a higher fuel consumption saving can be expected.

Despite the abundant potential benefits, it is necessary to conduct some cost and benefit analysis in locating the optimal ranges of traffic flow and capacity for the various scenarios of mixed operating traffic, in which different proportions of automated and conventional vehicles are assumed to cruise on the same AHS lane. The selection of input factors will greatly affect the cost and benefit functions so that the optimal range and the corresponding net benefit can vary to a large extent for various mixed traffic operations. The market penetration of AHS vehicles, technical development trends, prices and durability of the associated electronic equipment, and maintenance cost of the physical infrastructure are only some examples of input factors that can affect the outcomes of the analysis. Moreover, the background factors on which the system will be implemented can bring along diverse results; the length of the AHS corridor and the selected hours for analysis will generate a very different picture in the amount of net benefits.

Medical and legal costs due to an AHS accident, pollution, or noise generated because of the AHS implementation are considered as social costs. The relief of congestion as more vehicles can be served over the same highway system should be counted as system benefits. As more cost and benefit factors are accommodated in the analysis, a more thorough view of the economic structure of various scenarios can be expected. Since the analysis will become more complicated and the information on all possible cost or benefit factors is limited at this stage of AHS design, the authors will select only a few input factors for the cost-benefit analysis.

Department of Civil and Environmental Engineering, University of Wisconsin at Madison, 2256 Engineering Hall, 1415 Engineering Drive, Madison, Wis. 53706.

COST STRUCTURE OF AHS CORRIDOR

In this model, two types of cost will be associated with the application of AHS: the system cost and the user cost. The production and operating cost of the AHS will be considered as the former, while the payment for in-vehicle equipment by users will be considered as the latter. The basic idea of the model is that the total cost will decrease as more vehicles share the mixed AHS system and the traffic flow grows. The user cost will stay constant for any traffic flow, since each user is supposed to pay the same for the in-vehicle equipment installed. All cost data will be converted to the same unit for comparison with the benefit, which is in the unit of per mile per annual peak hour. In other words, it is in the dollar value that will be spent on each mile, 6 peak-hr each day, in a year. All the cost data are expressed in 1995 dollars after the introduction of a 6 percent discount rate, which will bring the future expenditures on the infrastructure back to present value.

The two application cases in the AHS operations are

- Case I: Dedicated AHS lane with dedicated entry/exit ramps, and
- Case II: Dedicated AHS lane with transition lane and common entry/exit ramps.

System Cost

System cost is composed of the costs of roadway infrastructure, traffic management center for AHS operation, and physical construction.

Cost of Roadway Infrastructure

The cost information of the operating packages of roadway infrastructure is shown in Table 1 (*1*). Nonrecurring expenditures are made up of fixed or lump-sum costs, such as the initial purchasing costs and the replacement expenditures on the packages along the years, whereas recurring expenditures include the variable costs, such as maintenance costs, of the packages. Since the nonrecurring expenditures are expressed as the total for the given year

TABLE 1 Cost Information of Operating Package of Roadway Infrastructure (*1*)

Roadway System Equipment	Non-Recurring Expenditures (in 1995$, 1000's)			Recurring Expenditures (in 1995$, 1000's)		
	Yr 0-5	Yr 6-10	Yr 11-20	Yr 5	Yr 10	Yr 20
Roadway System for AHS	0	0	6000	0	0	0

range, the annual expenditure for the roadway system for AHS between Years 11 and 20 is equal to $600,000 before introducing the discount factors. For Case I, the total expenditure will be $2,465,901 at Year 0, after discounting the total expenditure by 6 percent. The corresponding mathematical expression can be shown as follows:

$$\frac{\sum_{i=1}^{10} \frac{\$600,000}{(1+r)^i}}{(1+r)^{10}} = \$2,465,901 \tag{1}$$

where r represents 6 percent and j represents Year 1 to 10, which corresponds to a year range of 11–20.

The data are based on a system functioning for the entire day. However, the authors prefer to express the cost for the peak hours only (3 hr in the morning peak and 3 hr in the afternoon peak). The yearly nonrecurring cost will be divided by 24 hr and the result multiplied by 6 hr so as to obtain the yearly peak-hour nonrecurring expenditure for the given corridor. The result will then be divided by 10 mi so as to have the cost expressed on per-mile basis. In other words, given a discount rate of 6 percent, the nonrecurring expenditure for the roadway system for AHS can be estimated as follows:

$$\frac{\$2,465,901 \times 6\text{ hr}}{20\text{ years} \times 24\text{ hr} \times 10\text{ mi}} = \$3,082.40\text{/yr-peak-hr/mi} \tag{2}$$

Thus, the average annual peak-hour expenditure on the nonrecurring costs of this equipment for the AHS corridor is $3,082.40/year/mi (based on 1995 $, annual peak-hour cost, per-mile basis, 6 percent discount rate). Here, it is assumed that the cost can be spread out evenly across the time unit. In other words, the operation cost of the system is distributed evenly across time, with no discrimination on the intensity of the system usage.

Cost of Traffic Management Center Operation

This cost sector includes the expenditures for operating the traffic management center (TMC), such as the payment for the personnel at the TMC. By using an estimation approach similar to the previous one, it is found that the recurring and nonrecurring expenditures are summed as $3,211.30/annual peak-hr/mi (based on 1995 $, annual peak-hour cost, per-mile basis, 6 percent discount rate).

Cost of Physical Infrastructure Construction

The construction activities include earthwork, retaining walls, bridges, pavement, drainage, and such. There is a difference between the construction costs for Cases I and II. Thus, it will be interesting to see the variation in the system costs and the total costs.

Construction Cost of AHS in Case I Scenario

The total construction cost of AHS physical infrastructure in Case I is summed as $304,169,987 (*2*). Since the cost shown is given on a 25-mi AHS corridor basis, the annual expenditure on construction, which contributes to the peak hour on per-mile basis in Case I, is calculated as follows:

$$\frac{\$304,169,987 \times 6\text{ hr}}{20\text{ years} \times 24\text{ hr} \times 25\text{ mi}} = \$152,085\text{/year/mi}$$

$$\text{(in 1995 \$, annual peak-period, per-mile basis)} \tag{3}$$

Construction Cost of AHS in Case II Scenario

The total construction cost of AHS physical infrastructure in Case II is summed as $249,286,809 (*2*). By using the similar approach, the annual expenditure on construction during peak hour for a corridor in Case II is $124,643.40/year/mi (in 1995 $, annual peak-period, per-mile basis).

Therefore, the total system costs, which correspond to the sum of the three cost parts in the preceding for a given corridor and an adoption of 6 percent discount rate, are $158,378.70 for Case I and $130,936.70 for Case II.

User Cost

In this analysis, the user cost includes the payment for the in-vehicle equipment, which will communicate with the roadside AHS infrastructure and execute the various functions of AHS. The equipment includes vehicle lateral control, vehicle longitudinal control, vehicle route guidance, and vehicle system for AHS.

It is assumed that the market penetration of AHS vehicles falls in the range between 0.1 and 2 percent of the total number of vehicles in a given urban area, which is assumed to be 2,500,000. Other assumptions are that the number of AHS vehicles is 50,000

(2 percent of total number of vehicles) during the 20-year time frame, and the number of operating vehicles is constant. With a similar approach to that used in calculating the nonrecurring and recurring expenditures for the roadway infrastructure under the system cost category, the estimation for the in-vehicle equipment cost, which is in the unit of annual peak-hour expenditures per vehicle, is found to be $26.70/annual peak-hr/mi for the 6 percent discount rate.

Benefit

Time saving will be considered as the only benefit factor in this paper. Given the speed-flow-density relationship formula for 100 percent AHS traffic system (*3*) and that for the 100 percent conventional traffic system, one will be able to derive a simplified relationship among speed, density, and flow for the 20, 50, and 80 percent mixed AHS traffic system. The basic traffic flow relationship for 100 percent AHS traffic is as follows:

$$q = kv = v_f k \left[1 - \left(\frac{k}{k_{j2}} \frac{n - Lk_{j2}}{n - Lk} \right)^4 \right] \tag{4}$$

where

- q = traffic flow;
- k = density;
- k_{j2} = jam density, estimated to be 164 veh/mi;
- v = speed;
- v_f = free-flow speed, assumed to be 60 mph;
- n = number of vehicles in a platoon, assumed to be 20; and
- L = length of vehicle, about 5 m in general.

The basic traffic flow relationship for 100 percent conventional traffic (*4*) is as follows:

$$q = kv = v_f k \left[1 - \left(\frac{k}{k_{j1}} \right)^{1.5} \right]^5 \tag{5}$$

where k_{j1} is jam density, estimated to be 260 veh/mi.

For a specific velocity, there will be a corresponding flow associated with it for both the 100 percent AHS and 100 percent conventional traffic cases. The flow for the mixed AHS system can be assessed roughly by adding the product of the mixed percentage (20, 50, or 80 percent AHS vehicles) and the difference between the two traffic flows for 100 percent AHS and 100 percent conventional traffic to the traffic flow of the 100 percent conventional traffic. For example, for $v = 6$ mph, the traffic flow q (100 percent AHS) of the 100 percent AHS case is 961.3 veh/hr, while the traffic flow q (100 percent conv) of the 100 percent conventional traffic case is 803 veh/hr. Then, the traffic flow for the 20 percent mixed traffic (20 percent AHS vehicles, 80 percent conventional vehicles) will be equal to

$$803 + 0.2(961.3 - 803) = 835 \text{ veh/hr} \tag{6}$$

The speed-flow relationship for the various combinations of conventional and AHS traffic is shown in Figure 1. The average velocity of the mixed AHS traffic stream can be obtained by dividing the traffic flow by the mixed density, which is numerically equal to the sum of the densities that are in the same proportion as the two 100 percent operating flows. The annual benefit can be estimated by multiplying the time difference in traveling 1 mi in the 100 percent conventional traffic scenario and the given mixed traffic scenario with 250 days (annual operating time period), 6 peak-hr, and $10/hr, which is assumed to be the average time value for travelers.

QUANTITATIVE ANALYSIS OF COST AND BENEFIT OF AHS CORRIDOR

In this section, the results of the cost-benefit analysis will be provided for various AHS system scenarios. The first three described scenarios will be referred to as Case I, in which the physical construction is provided with a dedicated AHS lane and dedicated entry/exit ramps; the last three will be referred to as Case II, in which the physical construction is provided with a dedicated AHS lane and transition lane with common entry/exit ramps. The cost will be discounted by a rate of 6 percent for all six scenarios.

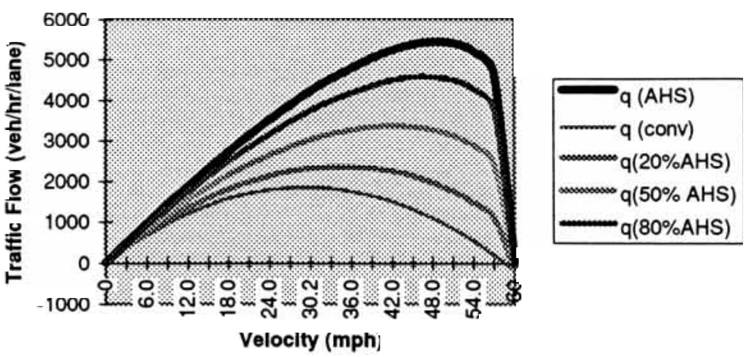

FIGURE 1 Flow-velocity relationship for different combinations of AHS and conventional traffic.

TABLE 2 Cost and Benefit Versus Traffic Volume in Case I (20 percent AHS)

Traffic Volume (veh/hr)	System Cost ($)	User Cost ($)	Total Cost ($)	Benefit ($)	Net Benefit ($)
465	340.9	26.7	367.7	420.0	52
835	189.8	26.7	216.5	503.7	287
1153	137.4	26.7	164.1	436.6	273
1431	110.7	26.7	137.5	353.2	216
1673	94.6	26.7	121.4	301.1	180
1885	84.0	26.7	110.8	259.4	149
2066	76.7	26.7	103.4	228.6	125
2219	71.4	26.7	98.1	197.7	100
2344	67.6	26.7	94.3	176.5	82
2442	64.9	26.7	91.6	156.1	64
2506	63.2	26.7	89.9	136.7	47
2542	62.3	26.7	89.1	119.5	30
2545	62.2	26.7	89.0	104.4	15
2515	63.0	26.7	89.7	92.1	2
2444	64.8	26.7	91.5	79.5	-12

In the first case, the hypothetical AHS corridor will be occupied by 20 percent AHS vehicles and 80 percent conventional vehicles; the relevant cost and benefit are estimated and illustrated in Table 2 and Figure 2. In the second scenario, the hypothetical AHS corridor will be occupied by 50 percent AHS vehicles and 50 percent conventional vehicles; the relevant cost and benefit are estimated and illustrated in Table 3 and Figure 3. The hypothetical AHS corridor will be occupied by 80 percent AHS vehicles and 20 percent conventional vehicles for the third case, and the relevant cost and benefit are estimated and illustrated in Table 4 and Figure 4.

In the fourth case, the hypothetical AHS corridor will be occupied by 20 percent AHS vehicles and 80 percent conventional vehicles; the relevant cost and benefit are estimated and illustrated in Table 5 and Figure 5. The hypothetical AHS corridor in the fifth scenario will be occupied by 50 percent AHS vehicles and 50 percent conventional vehicles; the relevant cost and benefit are estimated and illustrated in Table 6 and Figure 6. In the final case, the hypothetical AHS corridor will be occupied by 80 percent AHS vehicles and 20 percent conventional vehicles, and the relevant cost and benefit are estimated and illustrated in Table 7 and Figure 7.

CONCLUSION AND FUTURE STUDY

For the six scenarios shown in this paper, the total cost decreases as a higher number of AHS and conventional vehicles operate in the system, since the operating cost can be shared by more entities. It is reasonable to observe that the total cost can reach the lowest in the 80 percent AHS scenario because more capacity can be handled in an hour. On the other hand, the benefit can reach its climax for the 80 percent AHS scenario, since this proportion of AHS traffic can generate the highest average velocity among the three mixed traffic cases. As a result, it can save time the most. The net benefit stays positive in different flow ranges for the six scenarios—for example, for Case 1, from about 460 to 2,500 veh/hr, whereas for Case 3, from

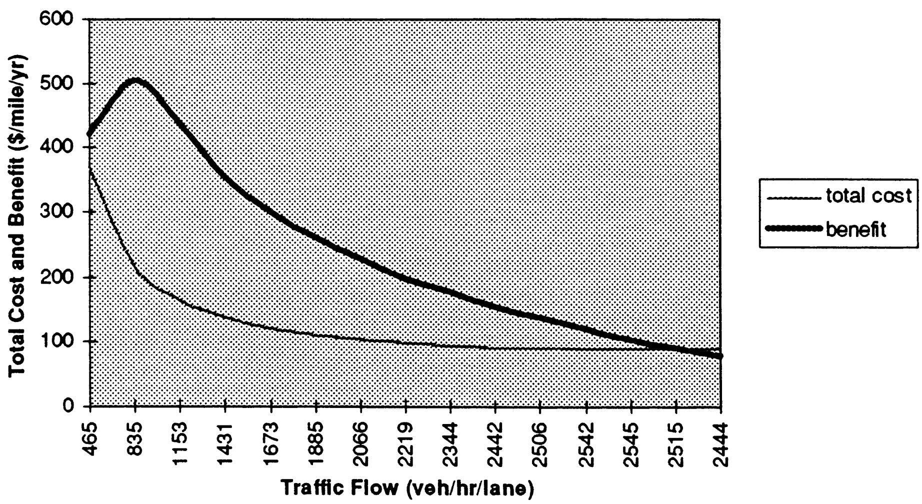

FIGURE 2 Cost and benefit versus traffic volume in Case I (20 percent AHS).

TABLE 3 Cost and Benefit Versus Traffic Volume in Case I (50 percent AHS)

Traffic Volume (veh/hr)	System Cost ($)	User Cost ($)	Total Cost ($)	Benefit ($)	Net Benefit ($)
473	335.0	26.7	361.7	1076.8	715
882	179.5	26.7	206.3	1492.8	1287
1254	126.3	26.7	153.0	1370.9	1218
1596	99.2	26.7	126.0	1186.7	1061
1911	82.9	26.7	109.6	1039.5	930
2200	72.0	26.7	98.7	912.8	814
2463	64.3	26.7	91.0	809.5	718
2703	58.6	26.7	85.3	711.6	626
2918	54.3	26.7	81.0	634.6	554
3110	50.9	26.7	77.7	562.5	485
3261	48.6	26.7	75.3	496.8	421
3387	46.8	26.7	73.5	436.7	363
3480	45.5	26.7	72.2	381.7	309
3535	44.8	26.7	71.5	336.3	265
3545	44.7	26.7	71.4	289.0	218
3498	45.3	26.7	72.0	244.9	173
3375	46.9	26.7	73.7	202.4	129
3137	50.5	26.7	77.2	159.4	82
2683	59.0	26.7	85.8	110.2	24
30	5279.3	26.7	5306.0	0.1	-5306

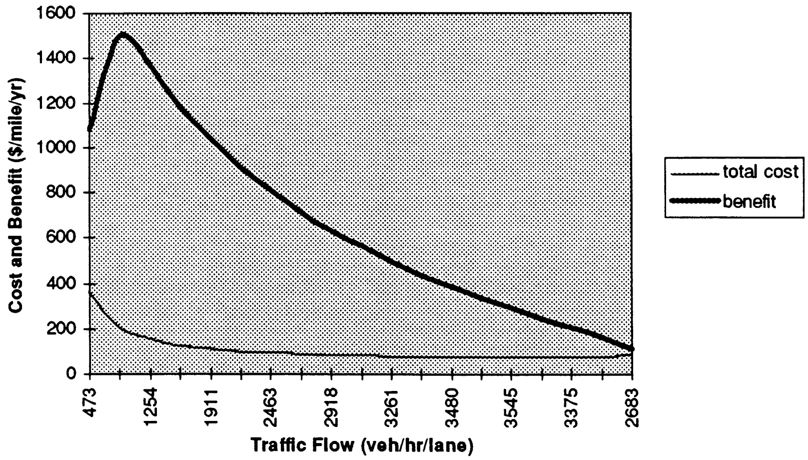

FIGURE 3 Cost and benefit versus traffic volume in Case I (50 percent AHS).

TABLE 4 Cost and Benefit Versus Traffic Volume in Case I (80 percent AHS)

Traffic Volume (veh/hr)	System Cost ($)	User Cost ($)	Total Cost ($)	Benefit ($)	Net Benefit ($)
481	329.2	26.7	355.9	1838.1	1482
930	170.4	26.7	197.1	2943.6	2746
1356	116.8	26.7	143.5	2922.2	2779
1762	89.9	26.7	116.6	2697.6	2581
2149	73.7	26.7	100.5	2455.5	2355
2515	63.0	26.7	89.7	2217.6	2128
2861	55.4	26.7	82.1	1999.4	1917
3188	49.7	26.7	76.4	1788.3	1712
3492	45.3	26.7	72.1	1602.1	1530
3778	41.9	26.7	68.7	1423.8	1355
4016	39.4	26.7	66.2	1265.2	1199
4232	37.4	26.7	64.2	1114.5	1050
4415	35.9	26.7	62.6	973.0	910
4556	34.8	26.7	61.5	846.2	785
4645	34.1	26.7	60.8	721.3	660
4668	33.9	26.7	60.7	602.8	542
4598	34.4	26.7	61.2	488.1	427
4382	36.1	26.7	62.9	374.3	311
3875	40.9	26.7	67.6	248.9	181
48	3299.6	26.7	3326.3	0.2	-3326

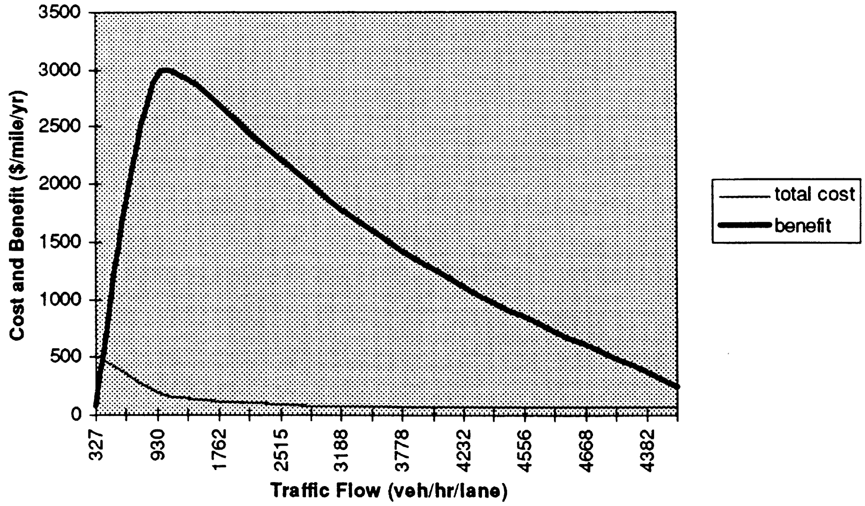

FIGURE 4 Cost and benefit versus traffic volume in Case I (80 percent AHS).

TABLE 5 Cost and Benefit Versus Traffic Volume in Case II (20 percent AHS)

Traffic Volume (veh/hr)	System Cost ($)	User Cost ($)	Total Cost ($)	Benefit ($)	Net Benefit ($)
465	281.9	26.7	308.6	420.0	111
835	156.9	26.7	183.6	503.7	320
1153	113.6	26.7	140.3	436.6	296
1431	91.5	26.7	118.3	353.2	235
1673	78.2	26.7	105.0	301.1	196
1885	69.5	26.7	96.2	259.4	163
2066	63.4	26.7	90.1	228.6	139
2219	59.0	26.7	85.7	197.7	112
2344	55.9	26.7	82.6	176.5	94
2442	53.6	26.7	80.4	156.1	76
2506	52.3	26.7	79.0	136.7	58
2542	51.5	26.7	78.3	119.5	41
2545	51.4	26.7	78.2	104.4	26
2515	52.1	26.7	78.8	92.1	13
2444	53.6	26.7	80.3	79.5	-1
2327	56.3	26.7	83.0	68.2	-15
2151	60.9	26.7	87.6	56.8	-31
1893	69.2	26.7	95.9	43.4	-53
1491	87.8	26.7	114.5	32.2	-82

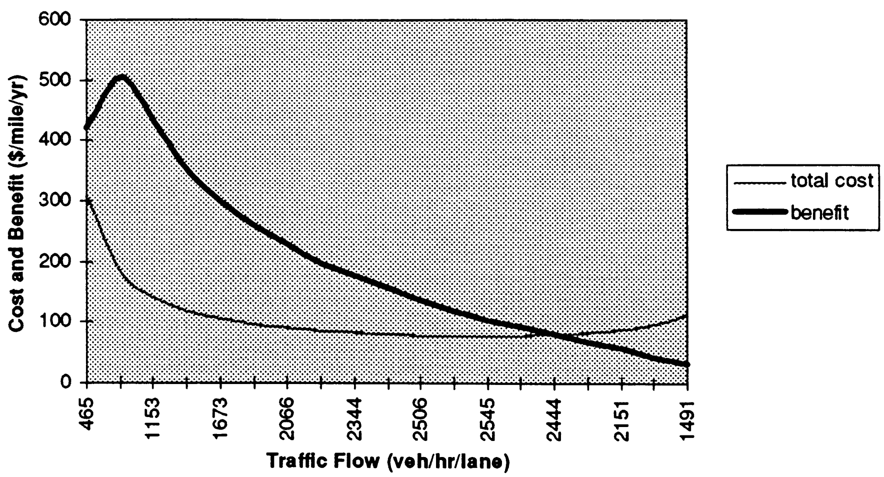

FIGURE 5 Cost and benefit versus traffic volume in Case II (20 percent AHS).

TABLE 6 Cost and Benefit Versus Traffic Volume in Case II (50 percent AHS)

Traffic Volume (veh/hr)	System Cost ($)	User Cost ($)	Total Cost ($)	Benefit ($)	Net Benefit ($)
473	276.9	26.7	303.7	1076.8	773
882	148.4	26.7	175.2	1492.8	1318
1254	104.4	26.7	131.1	1370.9	1240
1596	82.0	26.7	108.8	1186.7	1078
1911	68.5	26.7	95.3	1039.5	944
2200	59.5	26.7	86.3	912.8	827
2463	53.2	26.7	79.9	809.5	730
2703	48.4	26.7	75.2	711.6	636
2918	44.9	26.7	71.6	634.6	563
3110	42.1	26.7	68.8	562.5	494
3261	40.2	26.7	66.9	496.8	430
3387	38.7	26.7	65.4	436.7	371
3480	37.6	26.7	64.4	381.7	317
3535	37.0	26.7	63.8	336.3	273
3545	36.9	26.7	63.7	289.0	225
3498	37.4	26.7	64.2	244.9	181
3375	38.8	26.7	65.5	202.4	137
3137	41.7	26.7	68.5	159.4	91
2683	48.8	26.7	75.5	110.2	35
30	4364.6	26.7	4391.3	0.1	-4391

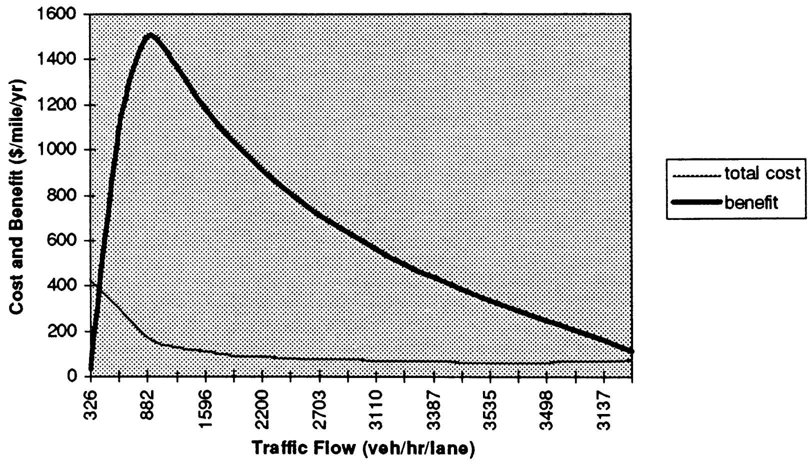

FIGURE 6 Cost and benefit versus traffic volume in Case II (50 percent AHS).

TABLE 7 Cost and Benefit Versus Traffic Volume in Case II (80 percent AHS)

Traffic Volume (veh/hr)	System Cost ($)	User Cost ($)	Total Cost ($)	Benefit ($)	Net Benefit ($)
481	272.2	26.7	298.9	1838.1	1539
930	140.9	26.7	167.6	2943.6	2776
1356	96.6	26.7	123.3	2922.2	2799
1762	74.3	26.7	101.0	2697.6	2597
2149	60.9	26.7	87.7	2455.5	2368
2515	52.1	26.7	78.8	2217.6	2139
2861	45.8	26.7	72.5	1999.4	1927
3188	41.1	26.7	67.8	1788.3	1721
3492	37.5	26.7	64.2	1602.1	1538
3778	34.7	26.7	61.4	1423.8	1362
4016	32.6	26.7	59.3	1265.2	1206
4232	30.9	26.7	57.7	1114.5	1057
4415	29.7	26.7	56.4	973.0	917
4556	28.7	26.7	55.5	846.2	791
4645	28.2	26.7	54.9	721.3	666
4668	28.0	26.7	54.8	602.8	548
4598	28.5	26.7	55.2	488.1	433
4382	29.9	26.7	56.6	374.3	318
3875	33.8	26.7	60.5	248.9	188
48	2727.8	26.7	2754.6	0.2	-2754

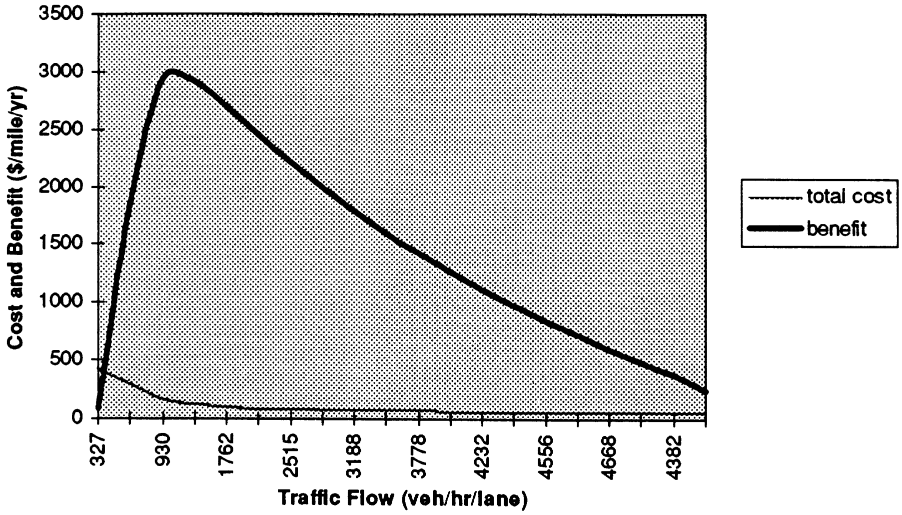

FIGURE 7 Cost and benefit versus traffic volume in Case II (80 percent AHS)

480 to 4,600 veh/hr. Also, it reaches different climax for different cases. It is demonstrated that, if a higher percentage of AHS vehicles are operating in the scene, the net benefit for each flow will be higher.

It can also be observed that the cost input of the two cases does not change the net benefit to a large extent, while the three mixed AHS scenarios will be much more sensitive in determining the size of the net benefit. In a future study, the authors will introduce a number of discount rates to study the changes in the net benefit. Fuel consumption saving because of smoother driving in the scenarios will be of interest, too. More cost data input that is regarded as essential to the operation will also be considered in the analysis, if the data are available, to portray a more complete picture.

REFERENCES

1. Joint Architecture Team, Loral Federal Systems, and Rockwell International. *ITS Architecture—Cost Analysis*. U.S. Department of Transportation, 1996.
2. Bechtel Corporation. Memorandum for Estimating External Standard Report by WBS—Case 1 and 2. Presented at AHS C2 Meeting, Richmond, Calif., 1996.
3. Ran, B., and H.-S. Jacob Tsao. Traffic Flow Analysis for an Automated Highway System. Presented at 75th Annual Meeting of the Transportation Research Board Washington, D.C., 1996.
4. May A. D. *Traffic Flow Fundamentals*. Prentice Hall, Englewood Cliffs, N.J., 1990.

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