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By Robert A. Johnston,[1] and Dorriah L. Page[2]

(Reviewed by the Highway Division)

Abstract: The automation of urban freeways is intended to reduce travel time costs, reduce direct (distance) costs, improve the safety of travel, create smoother vehicle operation, increase freeway lane capacity, and improve the comfort of travelers. This study performs a financial analysis of the first four of these effects of automation on present urban travelers by estimating the financial costs of automating vehicles (net of the savings on fuel and insurance), and calculating the break-even values for the speed increases needed to offset these costs. The analysis shows that automation will benefit heavy trucks and buses. Automation will also be cost-effective for auto commuters if large, but plausible, freeway speed increases can be obtained. Automation in the future (when nonautomated freeway speeds will be lower) will be beneficial for more users, since the break-even speed increases will be lower than their present values. The results of this analysis are very sensitive to assumptions regarding the cost of the automation devices and the changes in annual insurance payments.

Introduction

Finding solutions to worsening traffic conditions in urban areas has long occupied those in transportation planning. Heavily traveled freeways are extremely congested during peak travel periods, and this delay is increasingly costly. The technical measure of congestion is the reduction in average speed relative to that possible under free-flow conditions (Altshuler 1979). Almost 12% of all freeway travel in urban areas occurs under conditions of recurring congestion. This level is predicted to rise to about 24% in 2005 (Lindley 1987). For the individual traveler, congestion is perceived primarily in terms of increased travel costs. Urban freeway congestion annually consists of over 1.2 billion vehicle-hours of delay, over 1.3 billion gallons of wasted fuel, and over $9 billion in user costs (Lindley 1987).

The barriers to implementing automation, as ranked by panelists in a study conducted by Underwood (1990), are: cost to the consumer, obtaining technical reliability, lack of demand, and government and manufacturer liability risks. Underwood states that the adoption of automation will depend on increased congestion, desires for improved safety and comfort, a demand for traffic information, declining costs for the technology, and the promise of shorter trip times.

According to Underwood, if automation can produce safety advantages, then the primary question becomes one of cost: cost to vehicle manufacturers, automobile insurance companies, and ultimately the vehicle owner.

Highway automation appeals to planners in that it promises increased capacity without building new freeways. Automation avoids political conflict with those who oppose new freeways. Highway automation is being studied

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currently with regard to both technological feasibility and social acceptance. For a history of automation research in the U S , see Johnston (1990).

To date, the Intelligent Vehicle Highway Systems (IVHS) America Task Force has been established in the U S The PROMETHEUS program in Europe and the corresponding Japanese AMTICS and RACS programs began in 1987 (Koshi 1988) The tardiness of the American governmental response has been attributed to the lack of cooperation on the part of the public and the private sectors, as well as the financial structure of U S. industry (Chen and Ervin 1990)

Highway automation consists of three functions navigation information and guidance, lateral control of vehicles within lanes, and longitudinal control of vehicles in succession If successful, automation will increase freeway capacity through shorter headways, smaller lane widths (and hence more lanes per cross section), higher speeds, and reduced nonrecurring congestion due to increased safety

Today's freeways attain a capacity of approximately 2,000 vehicles/hour/lane with traffic at 35-55 mph (kph = 1.61 mph) Automated lanes, operating at 60 mph with a vehicle headway of 0 5 seconds, could potentially increase this capacity to over 7,200 vehicles per hour per lane, and maintain high speeds by metering access (*Highway* 1965)

METHODS

Capacity is a public objective, but is ignored by the individual traveler The traveler seeks to lower his or her time and distance costs In this study, we estimate the costs of automating vehicles, and then solve directly for the speed increases and resultant travel time savings that equal these costs Since this is a financial analysis from the viewpoint of potential users, we do not examine public costs and changes to the infrastructure Increasing the number of lanes by narrowing them is not considered in our analysis, as travelers do not consider roadway capacity, per se, in their travel and vehicle purchase decisions

Distance savings due to improved route funding and time savings due to fewer accidents are represented in the overall time-savings results Savings on fuel from smoother operation and savings on insurance are netted out of the costs of automation

Repair costs for vehicles are predicted to decrease due to the mechanized control of acceleration and deceleration This cost decrease is included in our reduced operation and maintenance cost assumptions for some cases Increased comfort is not included in our analysis This issue is problematic, due to the short vehicle following distances, which may be uncomfortable for many occupants

We estimate time costs for each vehicle type and trip type on U S urban freeways For each class of vehicle and trip type, we estimate the speed increases and the corresponding time savings necessary on the average freeway trip to break even with the extra annual cost of owning the on-board automation equipment

After presenting the average break-even results in the tables and text, we consider special cases We estimate the break-even time savings for large urban areas, for drivers with higher incomes, and for the case of lower future travel speeds on nonautomated freeways We also factor the results for commuting and recreational trips to account for vehicle occupancy over 1 0, which increases time savings per trip

The commute, recreation, and work trip time-cost values for light duty vehicles were calculated from the average national wage rate of $8 57 per hour (1984 dollars). A prevailing wage rate of $12.00 per hour was used for heavy- and medium-truck operators, and $9 50 per hour for bus operators (1984 dollars) (*Prevailing* 1984) Only the commute trip and recreation trip-time cost values apply to the light vehicles, because they are seldom used for work [about 4% of their VMT is for work trips, (*Summary* 1985)] Only the work trip time-cost value applies to the heavy vehicles.

The average urban work trip time-cost is approximated by the national wage rate ($8 57 per hour in 1984 dollars) The commute trip hourly time cost is two-thirds of this value ($5 65 per hour), and the recreation trip time cost is one-fourth ($2 14 per hour) (Winston 1985) Average annual time costs on urban freeways were then calculated by multiplying the hours per year spent on urban freeways for each vehicle type (*Summary* 1985) by the cost per hour of each trip type Past federal policy (*Procedures* 1989) required the use of lower values (25%, 10%) for work trip and other trip values of time To be favorable to automation, we chose the higher values as found in the economics literature

There are eight types of vehicles for which calculations were performed small, intermediate, and large automobiles, vans, light, medium, and heavy trucks, and buses Vehicles were distinguished by their gross vehicle weight (GVW) Small cars are defined as those vehicles with standard equipment weighing 3,000 lb or less Intermediate cars weigh less than 3,500 lb and large cars weigh more than 3,500 lb Vans include those vehicles weighing 5,000 lb or less Light trucks include recreational trucks at 6,000 lb or less Heavy trucks are defined as combination, multiple-axle freight vehicles consisting of a power unit (a truck tractor), and one or two trailing units (a semitrailer) of 10,000 lb or more The most frequently used combination is popularly referred to as a tractor-trailer Medium trucks are those that fall between the GVW of light and heavy trucks (*Summary* 1985)

Cost Estimates

Tables 1–4 show our estimates of the annual cost of automating a vehicle There are eight vehicle types under four sets of cost conditions perceived and actual changes in annual costs, pertaining to both new and already owned vehicles Perceived changes in annual costs include the cost of adding

TABLE 1 New Vehicle Perceived Changes in Annual Costs (in 1984 Dollars)

Cost category (1)	Estimate bound (2)	Small ($) (3)	Medium ($) (4)	Large ($) (5)	Van ($) (6)	Light truck ($) (7)
		Type of Light Vehicle				
Cost of automation devices (annualized for five years)	High	200	200	200	200	200
	Low	100	100	100	100	100
Maintenance costs of automation devices	High	100	100	100	100	100
	Low	50	50	50	50	50
Total perceived costs	High	300	300	300	300	300
	Low	150	150	150	150	150

Cost category (1)	Estimate bound (2)	Type of Light Vehicle: Small (3)	Medium (4)	Large (5)	Van (6)	Light truck (7)
Cost of automation devices (annualized for three years)	High	433	433	433	433	433
	Low	266	266	266	266	266
Maintenance costs of automation devices	High	100	100	100	100	100
	Low	50	50	50	50	50
Total perceived costs	High	533	533	533	533	533
	Low	316	316	316	316	316

the automation device to the vehicle and the subsequent cost of maintenance for the device Actual changes include all changes in annual costs for each vehicle type, and include not only the cost of the automation device and its maintenance, but changes in fuel costs, changes in operation and maintenance costs for medium and heavy trucks and buses, changes in insurance and registration costs for each vehicle, and the salvage value of the automation devices All values are in 1984 dollars, the latest year for which we could compile complete data We project high and low values for each of these cost factors, due to uncertainty After a thorough literature search (Johnston et al 1990, PATH database at the Institute of Transportation Studies, University of California, Berkeley 1989, Stafford 1990, Chen and Irvin 1990) we found one set of estimates (Systems 1982) This FHWA study projected costs of about $2,500/year for light-duty vehicles, including roadway costs About $1,500/year of this was for vehicle costs This is about three times the high values used by us Route guidance devices alone are estimated to cost about $500 (Dedicated 1986)

The costs of adding the automation devices to new and existing vehicles were estimated by the writers and annualized An interest rate was not included, as the time periods were short five years for light-duty new vehicles, and three years for light-duty existing vehicles These short periods reflect our assumptions of vehicle turnover and rapid technological obsolescence Heavy trucks are replaced between 500,000 and 850,000 mi (approximately 10 years) (Amalitano, personal communication, 1991) Buses owned by agencies that follow federal guidelines are replaced around 12 years or 500,000 mi, whichever comes first (Amalitano, personal communication, 1991) For this study, we annualized payments for heavy-duty vehicles at 10 years for new vehicles and five years for existing vehicles

Fuel costs for the actual cost tables were obtained for each light-vehicle type in cents per mile (*Summary* 1985) and converted to dollars per year by multiplying by the total number of miles traveled per year The miles traveled per year by each vehicle type were available from national transportation statistics, as were values for operating costs (*Summary* 1985)

We estimated full operation and maintenance costs for medium and heavy trucks and for buses, as these vehicles are used only for business purposes and the owners consider full costs (including overhead) in their decision-

TABLE 3 New Vehicle Actual Changes in Annual Costs (in 1984 Dollars)

Cost category (1)	Estimate bound (2)	Type of Light Vehicle: Small ($) (3)	Medium ($) (4)	Large ($) (5)	Van ($) (6)	Light truck ($) (7)	Type of Heavy Vehicle: Medium ($) (8)	Heavy ($) (9)	Bus ($) (10)
Cost of automation devices (annualized for five yrs LD/10 yrs HD)	High	200	200	200	200	200	300	300	30
	Low	100	100	100	100	100	200	200	20
Maintenance costs of automation devices	High	100	100	100	100	100	200	1,000	1,00
	Low	50	50	50	50	50	100	500	50
Fuel/operation and maintenance costs	High	0	0	0	0	0	0	0	[illegible]
	Low	−15	−18	−23	−26	−28	−225	−490	−2,12
Insurance payments	High	100	100	100	100	100	500	1,000	1,00
	Low	−100	−100	−100	−100	−100	−500	−1,000	−1,00
Registration fees	High	25	25	25	25	25	30	0	[illegible]
	Low	0	0	0	0	0	0	0	[illegible]
Salvage value of automation device	High	0	0	0	0	0	0	0	[illegible]
	Low	−20	−20	−20	−20	−20	−40	−80	−8
Total actual costs	High	425	425	425	425	425	1,030	2,300	2,30
	Low	15	12	7	4	2	−465	−870	−2,50

TABLE 4. Existing Vehicle Actual Changes in Annual Costs (in 1984 Dollars)

Cost category (1)	Estimate bound (2)	Type of Light Vehicle: Small ($) (3)	Medium ($) (4)	Large ($) (5)	Van ($) (6)	Light truck ($) (7)	Type of Heavy Vehicle: Medium ($) (8)	Heavy ($) (9)	Bus ($) (10)
Cost of automation devices (annualized for three yrs LD/5 yrs HD)	High	433	433	433	433	433	666	700	700
	Low	266	266	266	266	266	500	500	500
Maintenance costs of automation devices	High	100	100	100	100	100	200	1,000	1,000
	Low	50	50	50	50	50	100	500	500
Fuel/operation and maintenance costs	High	0	0	0	0	0	0	0	0
	Low	−15	−18	−23	−26	−25	−233	−490	−2,120
Insurance payments	High	100	100	100	100	100	500	1,000	1,000
	Low	−100	−100	−100	−100	−100	−500	−1,000	−1,000
Registration fees	High	25	25	25	25	25	30	0	0
	Low	0	0	0	0	0	0	0	0
Salvage value of automation device	High	0	0	0	0	0	0	0	0
	Low	−50	−50	−50	−50	−50	−100	−166	−166
Total actual costs	High	658	658	658	658	658	1,396	2,700	2,700
	Low	151	140	143	140	141	−223	−656	−2,286

making (*Summary* 1985) We assume that owners of autos and light trucks consider only fuel costs as their operation and maintenance costs in their decisions regarding automation (Chen and Ervin 1990)

Automation will result in smoother travel (fewer stops and starts), which will decrease fuel consumption Therefore, the low value for fuel consumption assumes a 20% savings in fuel on freeways As approximately 20% to 30% of the total vehicle miles traveled (VMT) for each vehicle type are on urban freeways (*Life* 1977), the annual fuel costs were reduced by 5% The low cost estimate of 5% fuel savings for heavy trucks and buses has added to it an additional 5% savings in operation and maintenance costs due to lessened wear on brakes and the drive train.

Insurance values were estimated from figures provided by several insurance agencies (California Transit Insurance Pool 1989, Farmers Insurance, personal communication, 1989, Unitrans, personal communication, 1989) As automation may provide safer travel, this safety should be reflected in reduced insurance costs However, insurance companies could raise rates, especially in the early years of automation, and so higher values were also used

Registration fees are predicted to increase for light vehicles and medium-duty trucks, since the value of the vehicle will increase due to the value of its automation devices The cost of the devices is approximately 1–2% of the value of these new vehicles (Table 3) It is somewhat higher (4–10%) for an existing vehicle (Table 4) We estimated a 10% increase in registration fees as a high value, and we posited no change in registration fees as the low value, to report the high-valuation case and also the case in which the automation equipment was exempted from vehicle valuations For heavy trucks and for buses, registration fees are based on unladen vehicle weight and will not be significantly affected (California Motor Vehicle Code, sec 9400)

The high salvage value for the automation devices was arbitrarily estimated to be one-fifth of their original value, due to depreciation of the devices Due to the difficulty of removing the devices from the vehicle, the low salvage value is projected to be zero

Tables 1 and 3 show our estimates of perceived and actual changes in annual costs for new vehicles In general, the actual costs were close to twice the perceived costs for the light vehicles Purchasers of light-duty vehicles may reach a decision on whether to automate based on perceived costs alone For heavy vehicles, only actual cost estimates are used, since the owners of these vehicles make decisions based on complete cost information

New vehicle perceived annual costs ranged from a high of $300 00 to a low of $150 00 for a small car Actual changes in annual costs for new vehicles ranged from a high of $425 00 to a low of $15 00 for a small car, and a high of $2,300 00 and a low of $ − 870 00 for a heavy truck This wide range is mainly a product of two variables fuel and maintenance costs, and insurance costs As vehicles such as buses spend up to $30,000 per year (with taxes) on fuel alone, it is clear why even a small percentage increase in fuel efficiency would create a large change in the annual cost of operating such vehicles

Some of the low-end cost totals result in actual cost savings for owning an automated vehicle, without even considering travel-time savings, mainly due to decreases in fuel, operation and maintenance, and insurance costs Thus it would pay the individual owner to buy an automated vehicle even tudinal control and the greater safety could still result in a net savings

Tables 2 and 4 include perceived cost and actual cost estimates for adding automation equipment to already-owned vehicles We assume that the cost of adding automation technology to existing vehicles will be higher than adding technology at the time of assembly Thus, the high and low values for these vehicles are higher than for new vehicles Fuel, operation and maintenance costs, insurance costs, and registration fees remain the same as for new vehicles The cost values for the existing vehicles are annualized over three years, reflecting the shorter life of the used vehicle and uncertainty about resale value of the automation device The salvage value of the devices is higher for the used vehicle, because the devices are only three years old, rather than five

Break-Even Calculations

These total perceived and actual cost calculations were then applied to the break-even tables (Tables 6–9) The break-even tables are presented in a similar format and under the same four conditions as the annual cost tables for new and existing vehicles for perceived and actual changes in vehicle costs The input data for the break-even tables appear in Table 5 Break-even results are calculated for the average annual time-savings fraction, average absolute time savings per trip, and the average freeway speed increases necessary so that the cost of automation will break even with the travel time savings benefits The two most readily understandable results are the break-even average freeway speed increase and the absolute time savings per trip

Miles per year on urban freeways were derived as a percentage of total VMT on urban freeways for each vehicle type from national averages (*Highway* 1985) Urban freeway speeds were available from national speed data by vehicle type (*Highway* 1985) Hours per year for each vehicle type on urban freeways were calculated by dividing the miles per year on urban freeways by the average speed values

The break-even average annual time-savings fractions are calculated as follows The extra cost of automation per year is divided by the average time costs per hour for each vehicle and trip type This number of hours is divided by the total hours of freeway driving per year to get a time-savings fraction the fraction of time savings necessary on urban freeway trips for the cost of automating a vehicle to equal the time cost savings

The break-even freeway speed increase was calculated using average commute speeds of 29 mph, average recreation travel speeds of 58 mph, and average work speeds of 50 mph (all for urban freeways) (*Statistical* 1984) The break-even values were calculated using these values for commute, recreation, and work speeds and multiplying by the break-even annual time-savings fraction for each vehicle and trip type

Average freeway trip length data was available for each trip type and vehicle type (Table 5), and was entered into the break-even tables as input data to calculate the absolute time savings necessary for the average trips Commute and recreation trips were examined for light vehicles, and only work trips were analyzed for heavy vehicles

Break-even absolute time savings per trip measures the amount of time savings necessary on the freeway portion of an average trip for automation to pay for itself These values were calculated by subtracting the amount of time spent per trip on an automated freeway from the amount of time

TABLE 5 New and Existing Vehicle Input Data 1984

Data category (1)	Type of Light Vehicle: Small (2)	Medium (3)	Large (4)	Van (5)	Light truck (6)	Type of Heavy Vehicle: Medium (7)	Heavy (8)	Bus (9)
Miles per year	9,809	9,809	9,809	9,809	9,974	11,664	61,031	30,666
(a) Miles per Hour								
Commute	29	29	29	29	29	N/A	N/A	N/A
Recreation	58	58	58	58	58	N/A	N/A	N/A
Work	N/A	N/A	N/A	N/A	N/A	50	50	50
(b) Hours per year								
Commute	338 0	338 0	338 0	338 0	343 0	N/A	N/A	N/A
Recreation	169 0	169 0	169 0	169 0	172 0	N/A	N/A	N/A
Work	N/A	N/A	N/A	N/A	N/A	233	1,220	613
Commute time value ($/hr)	5 65	5 65	5 65	5 65	5 65	N/A	N/A	N/A
Recreation time value ($/hr)	2 14	2 14	2 14	2 14	2 14	N/A	N/A	N/A
Work time value ($/hr)	N/A	N/A	N/A	N/A	N/A	12 00	12 00	[illegible]
(c) Average Time Costs								
Commute	955 5	955 5	955 5	955 5	971 6	N/A	N/A	N/A
Recreation	361 9	361 9	361 9	361 9	368 0	N/A	N/A	N/A
Work	N/A	N/A	N/A	N/A	N/A	2,799	18,052	5,826
(d) Average Freeway Trip Length (Miles)								
Commute	9 9	9 9	9 9	9 9	9 9	N/A	N/A	N/A
Recreation	10 6	10 6	10 6	10 6	10 6	N/A	N/A	N/A
Work	N/A	N/A	N/A	N/A	N/A	11 4	11 5	[illegible]

TABLE 6 New Vehicle Break-Even Calculations (Perceived Costs)

Cost category (1)	Estimate bound (2)	Type of Light Vehicle: Small (3)	Medium (4)	Large (5)	Van (6)	Light truck (7)
Cost of automation ($)	High	300	300	300	300	300
	Low	150	150	150	150	150
(a) Average Time Savings Fraction						
Commute	High	0 31	0 31	0 31	0 31	0 31
	Low	0 16	0 16	0 16	0 16	0 15
Recreation	High	0 83	0 83	0 83	0 83	0 82
	Low	0 41	0 41	0 41	0 41	0 41
Work	High	N/A	N/A	N/A	N/A	N/A
	Low	N/A	N/A	N/A	N/A	N/A
(b) Freeway Speed Increase (Mph)						
Commute	High	9 1	9 1	9 1	9 1	8 9
	Low	4 5	4 5	4 5	4 5	4 4
Recreation	High	48 1	48 1	48 1	48 1	47 2
	Low	24 0	24 0	24 0	24 0	23 6
Work	High	N/A	N/A	N/A	N/A	N/A
	Low	N/A	N/A	N/A	N/A	N/A
(c) Absolute Time Savings (Hrs/Trip)						
Commute	High	0 08	0 08	0 08	0 08	0 08
	Low	0 05	0 05	0 05	0 05	0 05
Recreation	High	0 08	0 08	0 08	0 08	0 08
	Low	0 05	0 05	0 05	0 05	0 05
Work	High	N/A	N/A	N/A	N/A	N/A
	Low	N/A	N/A	N/A	N/A	N/A

that would have been spent per trip on an nonautomated freeway These calculations were performed by subtracting the trip miles divided by the automated speed from the trip miles divided by the nonautomated speed The automated speed was derived from the break-even freeway speed increase added to the nonautomated average speed for each trip type

Results

Table 6 shows the new vehicle, perceived costs break-even results The values for the cost of automation were taken from Table 1 The first break-even result is the average annual time-saving fraction for trips on urban freeways For automobiles, vans, and light trucks, for automation to pay off under perceived cost conditions, a time savings of 15–31% is necessary for commute travel For recreational travel (about two-thirds of light vehicle mileage), time savings of 41–83% are necessary

These percent time savings are then converted to freeway speed increases Light vehicles need to increase their freeway speeds by 4 4–9 1 mph for commute trips, and by 23 6–48 1 mph for recreational trips

Break-even absolute time savings per trip range from a break-even time

TABLE 7 Existing Vehicle Break-Even Calculations (Perceived Costs)

Cost category (1)	Estimate bound (2)	Type of Light Vehicle: Small (3)	Medium (4)	Large (5)	Van (6)	Light truck (7)
Cost of Automation ($)	High	533	533	533	533	533
	Low	316	316	316	316	316
(a) Average Time Savings Fraction						
Commute	High	0 56	0 56	0 56	0 56	0 55
	Low	0 33	0 33	0 33	0 33	0 33
Recreation	High	1 47	1 47	1 47	1 47	1 45
	Low	0 87	0 87	0 87	0 87	0 86
Work	High	N/A	N/A	N/A	N/A	N/A
	Low	N/A	N/A	N/A	N/A	N/A
(b) Freeway Speed Increase (Mph)						
Commute	High	16 1	16 1	16 1	16 1	15 9
	Low	9 6	9 6	9 6	9 6	9 4
Recreation	High	85 4	85 4	85 4	85 4	84 0
	Low	50 6	50 6	50 6	50 6	49 8
Work	High	N/A	N/A	N/A	N/A	N/A
	Low	N/A	N/A	N/A	N/A	N/A
(c) Absolute Time Savings (Hrs/trip)						
Commute	High	0 12	0 12	0 12	0 12	0 12
	Low	0 08	0 08	0 08	0 08	0 08
Recreation	High	0 11	0 11	0 11	0 11	0 11
	Low	0 09	0 09	0 09	0 09	0 09
Work	High	N/A	N/A	N/A	N/A	N/A
	Low	N/A	N/A	N/A	N/A	N/A

savings per trip of 0 05–0 08 hours (3 0–4 8 min) for cars, vans and light trucks, coincidentally, for both commute and recreational trips

Value of time savings less than 5 min, however, may not affect travel decisions (Stopher 1973) Average recreation and commute trip savings may need to be larger than indicated to affect behavior, regardless of vehicle occupancy rates

For existing vehicles under perceived cost conditions (Table 7), the break-even values are higher, due to the increased cost of adding the aftermarket automation technology to a vehicle

For new vehicles, actual costs (Table 8), the percent of annual time savings ranges between 0% and 44% for light vehicles on commute trips Recreation trips require an annual time savings of between 1% and 117% For new heavy vehicles on work trips, several interesting values resulted For these vehicles, the range of time savings was 37% to −17% for medium-duty trucks, 16% to −6% for heavy-duty trucks, and 40% to −43% for buses These values indicate that medium and heavy trucks and buses can experience speed decreases and automation may still pay off These results are due to the large savings in operation costs for heavy trucks and buses, due to smoother operation and large annual mileage (Table 5)

The range of break-even absolute freeway speed increases for new ve-

TABLE 8 New Vehicle Break-Even Calculations (Actual Costs)

Cost category (1)	Estimate bound (2)	Type of Light Vehicle: Small (3)	Medium (4)	Large (5)	Van (6)	Light truck (7)	Type of Heavy Vehicle: Medium (8)	Heavy (9)	Bus (10)
Cost of automation ($)	High	425	415	425	425	425	1,030	2,300	2,300
	Low	15	12	7	4	2	−465	−870	−2,500
(a) Average Time Savings Fraction									
Commute	High	0 44	0 44	0 44	0 44	0 44	N/A	N/A	N/A
	Low	0 02	0 01	0 01	0 00	0 00	N/A	N/A	N/A
Recreation	High	1 17	1 17	1 17	1 17	1 15	N/A	N/A	N/A
	Low	0 04	0 03	0 02	0 01	0 01	N/A	N/A	N/A
Work	High	N/A	N/A	N/A	N/A	N/A	0 37	0 16	(
	Low	N/A	N/A	N/A	N/A	N/A	−0 17	−0 06	−(
(b) Freeway Speed Increase (Mph)									
Commute	High	12 9	12 9	12 9	12 9	12 6	N/A	N/A	N/A
	Low	0 46	0 36	0 31	0 12	0 06	N/A	N/A	N/A
Recreation	High	34 05	34 05	34 05	34 05	33 49	N/A	N/A	N/A
	Low	1 20	1 20	1 20	0 32	0 16	N/A	N/A	N/A
Work	High	N/A	N/A	N/A	N/A	N/A	18 4	7 8	1(
	Low	N/A	N/A	N/A	N/A	N/A	−8 3	−2 9	−2
(c) Absolute Time Savings (Hrs/trip)									
Commute	High	0 11	0 11	0 11	0 11	0 11	N/A	N/A	N/A
	Low	0 01	0 00	0 00	0 00	0 00	N/A	N/A	N/A
Recreation	High	0 10	0 10	0 10	0 10	0 10	N/A	N/A	N/A
	Low	0 01	0 01	0 00	0 00	0 00	N/A	N/A	N/A
Work	High	N/A	N/A	N/A	N/A	N/A	0 06	0 03	(
	Low	N/A	N/A	N/A	N/A	N/A	−0 05	−0 01	−(

TABLE 9 Existing Vehicle Break-Even Calculations (Actual Costs)

Cost category (1)	Estimate bound (2)	Type of Light Vehicle: Small (3)	Medium (4)	Large (5)	Van (6)	Light truck (7)	Type of Heavy Vehicle: Medium (8)	Heavy (9)	Bus (10)
Cost of automation ($)	High	658	658	658	658	658	1,396	2,700	2,700
	Low	151	140	143	140	141	−223	−656	−2,286
(a) Average Time Savings Fraction									
Commute	High	0 69	0 69	0 69	0 69	0 68	N/A	N/A	N/A
	Low	0 16	0 16	0 16	0 16	0 15	N/A	N/A	N/A
Recreation	High	1 82	1 82	1 82	1 82	1 79	N/A	N/A	N/A
	Low	0 42	0 42	0 42	0 42	0 38	N/A	N/A	N/A
Work	High	N/A	N/A	N/A	N/A	N/A	0 50	0 19	0
	Low	N/A	N/A	N/A	N/A	N/A	−0 08	−0 04	−0
(b) Freeway Speed Increase (Mph)									
Commute	High	19 9	19 9	19 9	19 9	19 6	N/A	N/A	N/A
	Low	4 5	4 5	4 5	4 5	4 2	N/A	N/A	N/A
Recreation	High	105	105	105	105	103	N/A	N/A	N/A
	Low	24 2	22 4	22 9	22 4	22 2	N/A	N/A	N/A
Work	High	N/A	N/A	N/A	N/A	N/A	24 9	9 39	23
	Low	N/A	N/A	N/A	N/A	N/A	−3 9	−2 24	−19
(c) Absolute Time Savings (Hrs/trip)									
Commute	High	0 14	0 14	0 14	0 14	0 14	N/A	N/A	N/A
	Low	0 05	0 05	0 05	0 05	0 05	N/A	N/A	N/A
Recreation	High	0 12	0 12	0 12	0 12	0 12	N/A	N/A	N/A
	Low	0 05	0 05	0 05	0 05	0 05	N/A	N/A	N/A
Work	High	N/A	N/A	N/A	N/A	N/A	0 08	0 04	0
	Low	N/A	N/A	N/A	N/A	N/A	−0 02	−0 01	−0

hicles under actual cost conditions (Table 8) is 0 06–12 9 mph for light vehicles on commute trips, and 0 16–34 05 mph for recreation trips The heavy vehicles could go slower or faster on freeways by about 20 mph and still break even The break-even projections for existing vehicles under actual cost conditions (Table 9) were higher than the values for new vehicles.

To reflect a state of higher congestion in the future, consider our results as they might change under conditions with the baseline (unautomated) speed of travel reduced by one-half Break-even freeway speed increases (mph) would be one-half of those necessary under present speed conditions Break-even absolute time savings would remain the same, of course These speed increases would be more feasible than those required at 1984 freeway speeds We do not consider the issue of merging across lanes with widely varying speeds in this paper Special merge lanes will be needed on mixed facilities

Calculations based only on data for selected metropolitan areas of over 1 million inhabitants (New York, Los Angeles, Chicago, Houston) were run to determine if automation is more financially feasible in these regions Average freeway miles per year per vehicle in these regions are about 25% higher than the national urban averages Urban freeway speeds, however, are reduced by only about 1 5 mph (*New York* 1988, *California* 1988, *County* 1988), and the break-even results for these regions were about 80% of the national average results

Another case was run to determine if vehicle owners in the upper quartile income group would be more likely to benefit financially because their time costs are higher (based on an average 1984 annual income of $50,640) (*Current* 1986) For these vehicle owners, break-even calculations showed necessary increases in freeway speeds of about one-half those for all drivers For a small car, the break-even commute speed increase (new vehicle, actual costs) dropped from 12 9 mph to 6 63 mph Recreation speed increases fell from a high of 34 05 mph to 17 46 mph

Vehicle occupancy rate could be considered as a factor affecting break-even freeway speeds and absolute time savings It is unclear if vehicle owners consider cost sharing with passengers when making vehicle-purchase decisions, so we implicitly assumed a vehicle occupancy of 1 0 in the tables Since some vehicle buyers may consider cost sharing among occupants, we include this factor here For most heavy-duty vehicles on work trips, occupancy rates are 1 0, and therefore are not a factor For light-duty vehicles on commute trips, costs may be perceived as per adult occupant For 1984, average commute occupancy for urban areas was 1 3 (*Personal* 1986) Average occupancy for recreational travel was 2 0, but as this recreational occupancy average includes children (over age 5), we recalculated our numbers from Tables 8 and 9 using 1 3 as an approximation of adult occupancy For new and existing vehicles and for perceived and actual costs, break-even freeway speed increases and absolute time savings dropped by 23% Also, occupancy would tend to make automation cost-effective for those medium and heavy-duty trucks usually occupied by two or more workers, such as utility-repair vehicles

One potential market for automation would be carpool-vehicle owners These owners could consider cost-savings in their vehicle purchase and equipment purchase decisions Carpool occupancy is above 2 0, and so favorable break-even values can be obtained (half of those in the tables) [illegible] so small commuters may not choose to automate, as drivers seem to be unresponsive to time savings of less than about 5 min (Stopher 1974, *A Manual* 1977)

Analysis

Automation will apparently be financially feasible for medium and heavy trucks and for buses It may be feasible for new light vehicles used primarily for commuting, especially in HOV lanes Recent studies indicate that the early adopters of IVHS may be selected trucking companies, and also courier services, police, and emergency rescue fleets, as they can make good use of route guidance and higher speeds to accomplish urgent missions (Chen and Ervin 1990)

For medium and heavy trucks and buses, speed increases may not be necessary In fact, for automation to pay off, speed could actually decrease under some cost assumptions

For new light vehicles under perceived cost conditions, commute freeway speed increases between 4 4 mph and 9 1 mph seem clearly feasible For recreational travel, however, speed increases between 23 6 mph and 48 1 mph do not seem clearly feasible (at off peak times) About two-thirds of the miles in the average light vehicle on urban freeways are for recreational trips, and so automation is unlikely to pay off for most of these owners

Results for metropolitan areas of over 1 million inhabitants indicate that the automation of freeways in these areas will be significantly more beneficial than in smaller urban areas Because of longer times spent on freeways, the results are more optimistic than the national urban averages

Automation for those who commute relatively long distances or have high incomes will pay off more easily than for average drivers This result is due to their higher time costs We expect, therefore, that wealthy suburban commuters will tend to be supportive of automation and may provide an early adopter market niche Recall, however, that we used values for travel time about 150% larger than those approved by UMTA If their values were used, automation would be unlikely to pay for light vehicles, even in commuting

In conclusion, we found that the automation of urban freeways will most likely initially attract participation by the owners of medium and heavy trucks and buses The automation of automobiles, vans, and light trucks will most likely pay off only for owners of vehicles used primarily for HOV commute trips, but the small absolute time savings may not attract large numbers of investors

Our analysis looked only at average urban area trip lengths and speeds by trip type In the next phase of our research, we are examining simulated trip length and speed by purpose, for peak and nonpeak periods, using a regional transportation systems model operated on Sacramento, California, data for the year 2010 This study will permit us to project the effects of freeway automation on all regional travel We will evaluate changes in trip costs for automated vehicles and for nonautomated vehicles (which benefit from the capacity increases on the automated lanes) Network modeling will permit us to evaluate the HOV commuter market We will not be able to evaluate heavy-duty vehicles used for the transport of goods, though, since they are not represented in this travel-demand model

Regional travel-demand modeling will raise a fundamental theoretical issue not addressed by this paper, namely the question of whether speeding up traffic saves travelers time Work by Zahavi (1979) and others (Ryan and Spear 1978, McLynn and Spielberg 1978) show that reducing trip times should not be counted as a benefit of highway improvements (page 18). Iterating congested trip speeds from assignment back through trip distribution until equilibrium is reached will simulate the trip length part of this effect in our model runs These simulations will project lower travel-cost savings than are found by examining individual travelers on freeways, as we did in this paper

Automation requires vehicle owners to purchase devices, and thus automation must pay off for a large number of vehicle owners Our preliminary examination of individual travelers shows that the potential markets may be rather small (medium and heavy-duty trucks, buses, some high-income commuters, some HOV commuters) In this work we did not look at public costs.

Automation will greatly increase freeway capacity, however, and could reduce the public cost of expanding highway capacity Therefore, it may be economically efficient for local and state governments to subsidize the purchase of automation devices, which will increase the acceptance of this technology We will also attempt to evaluate this critical issue in our further research

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