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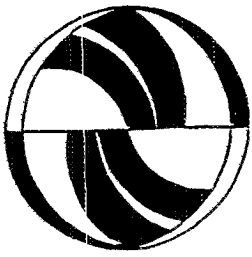
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The University of California
Transportation Center

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Automating Urban Freeways: Policy Research Agenda

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AUTOMATING URBAN FREEWAYS: POLICY RESEARCH AGENDA^a

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(Reviewed by the Urban Transportation Division)

ABSTRACT Population growth, continuing suburbanization, and higher labor-force participation rates, combined with a virtual halt in new freeway construction, have led to rapid increases in traffic congestion in the U S. This congestion is costly, for example the cost of highway congestion in the Los Angeles region is estimated to be \$3.6 billion per year. Roughly half of this congestion is estimated to be caused by incidents, and 63% is on freeways. In the future, planners project that congestion will increase dramatically and that the proportion of delay on surface streets will increase, as congestion spreads. Automated freeways have been proposed as a solution to urban traffic congestion. Paper describes the staged development of automated urban freeways and then suggests a series of research topics related to the major policy issues of road capacity, air quality, noise, safety and liability, cost and equity, privacy and organizational complexity. These difficult questions should be resolved before public acceptance for the technology is sought. Policy research on these matters should be carried out before or at the same time as the technology is being developed.

INTRODUCTION

Population growth, continuing suburbanization, and higher labor-force participation rates, combined with a virtual halt in new freeway construction, have led to rapid increases in traffic congestion in the U S. This congestion is costly, for example, the cost of highway congestion in the Los Angeles region is estimated to be \$3.6 billion per year (Draft 1987). Roughly half of this congestion is estimated to be caused by incidents, and 63% is on freeways. In the future, planners project that congestion will increase dramatically and that the proportion of delay on surface streets will increase, as congestion spreads.

Traditional solutions may not be effective. It is unlikely that many new freeway segments can be built in most metropolitan areas, due to cost and political opposition. Public transit requires unpopular subsidies, is becoming increasingly incompatible with suburban land-use patterns, and is losing riders nearly everywhere. The innovative proposal to charge tolls during rush periods is not a popular idea.

Highway automation is an appealing concept because it promises increased capacity without building new freeways. It is a technical fix that allows con-

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tinued use of automobiles, may reduce accident rates, and could reduce driver stress. But will these benefits be realized? We sketch a pathway of technological development and consider policy issues that arise. We focus on freeways in urban areas, because this is the locus of the worst congestion problems.

Automation encompasses three sets of technologies: (1) Navigational information so that vehicles can follow optimal routes, (2) automated lateral control of vehicles (steering), and (3) longitudinal control through automated acceleration and braking. The potential for increased capacity results from narrower lanes due to better lateral control, reduced headways between vehicles due to faster braking, and higher average speeds due to fewer accidents and smoother flows.

Several states are performing long-range research on the automation of rural freeways, urban freeways, and urban arterials. Freeway automation was studied in the 1950s by GM and RCA, in the 1960s by Ohio State University (Fenton 1970) and others, and in the 1970s by DOT and GM (Transportation Research Board 1976). These earlier efforts faded because of changing federal priorities (Shladover 1989). The present paper draws on these early analyses and more recent work to identify policy questions that require attention. These ideas were outlined in Johnston et al. (1988a, 1988b).

The present paper is not an examination of technical feasibility. We assume that the necessary roadway automation technologies will become practical and, instead, we focus our attention on the consequent systems-level effects of automation on traffic congestion, air pollution, noise, privacy, safety, economics, and equity. Our emphasis is on private auto and truck trips, which constitute the vast majority of trips, but we also briefly discuss the possible role of automated buses. No policy analysis has been performed, as evidenced by a late 1988 bibliography (Program 1988). Shladover (1989) outlines a few of the issues we cover.

AUTOMATION CONCEPT

We consider a conceptual urban freeway system with dual-mode vehicles operating at speeds of up to 100 mph (44.7 m/s) at headways of as little as 0.3 sec under on-board and roadside computer control. These characteristics permit, at least from a technical standpoint, substantially higher throughput per lane than present systems [flow rates of up to 1,000 vehicles/hr/lane (vphpl) versus the current maximum of about 2,000-2,500 vphpl]. We assume no new freeway- or ramp-lane additions in order to examine the pure automation case. The vehicles can be manually operated on surface streets and nonautomated freeway lanes.

We propose a set of steps for implementing such a system and identify problems that need to be investigated at each stage of development. Because the automated system will share roadways with standard autos during the early stages, the steps must be carefully planned. Gradual phasing in over a period of years is essential to minimize disruption to the existing transportation network.

Stage 1: Voluntary On-Board Navigation and Route Guidance Devices

The first stage of a transition to automation applies navigation technologies that can be installed in a conventional vehicle and that require only

limited or no action by government agencies. The devices can be for navigation only, such as the ETAK system. In this kind of system, onboard maps displayed on a screen provide accurate location information and are useful for drivers unfamiliar with an area.

Route-guidance systems are more complex. They are integrated with real-time traffic information to permit a driver to avoid congested regions, accidents, and so forth. This kind of system requires collection of traffic information to vehicles throughout a region and a means of transmitting the information to vehicles. Route guidance could also be used to find empty parking spaces. These systems could be almost entirely private. We could expect rental vehicles and delivery fleets to be among the first adopters of this technology, because these vehicles have a need for this information. French (1988) reviews the history of route guidance and navigation technologies. Koshi (1988) reviews efforts in Japan.

Stage 2: On-Board Longitudinal Control

This stage would automate the vehicle's braking system, which would then perform as a backup to the driver. Longitudinal control uses a radar-like system to control the accelerator and the brake and assures that a vehicle will slow or stop before running into a vehicle ahead. Such a system would not greatly increase lane throughput, because neither speed nor headways would be changed. It may, however, reduce congestion by reducing accidents.

Stage 3: Lateral Control and Dedicated Lanes

In the next stage, freeway lanes would be dedicated to autonomous automated (stage 2) vehicles only. The speed and spacing of the vehicles would be under the control of each vehicle, but automated longitudinal control would permit the reduction of headways and increases in average speeds. Headways will be limited, however, by dynamic-flow oscillations among the autonomous vehicles and by response-time lags in their braking systems.

Lateral control automates vehicle steering. Most of the technology would probably be in the vehicle. Some kind of device may be needed on the freeway to provide lateral locational information. Methods will have to be found to create gaps in adjacent nonautomated lanes for vehicles to merge right into mixed traffic. Merging left into automated lanes may also present problems. Automated express buses and also trucks could operate in automated lanes, along with autos. To maintain high speeds and densities on hills, it may be necessary to require minimum performance characteristics as a condition for access to the automated lanes. Methods will have to be found to keep nonautomated vehicles out of the dedicated lanes. This stage will free up drivers' time by taking over their duties on the freeway. Executives would likely be early adopters, as well as workers who spend a lot of time on freeways, such as real-estate developers, realtors, building inspectors, salespersons, delivery drivers, truckers, bus drivers, and taxi drivers.

Stage 4: Full Automation of Some Lanes

Stage 4 requires a major break with the established highway system. Roadway computers will coordinate the participating vehicles, resulting in 1 sec headways or less and flow rates of 3,600 vehicles/hr or more in the auto-

ated lanes. Flow will only be limited by time lags in the braking systems. Only automated vehicles will be permitted to use the left-hand lanes. The driver will be allowed to control the vehicle only after it has left the automated lane. Automated vehicles will enter the freeway with the nonautomated vehicles and move left to the dedicated lanes. As more vehicles are equipped with devices, additional lanes would be automated.

Stage 5: Full Automation of All Lanes

Only automated vehicles will be allowed on the urban portions of the freeway system. High flow rates ideally will occur in all lanes, except the right-hand merge lane. It is possible that drivers could make reservations to enter the freeway on special ramp lanes and for parking at their destinations. The parking-reservation system could be privately run.

Our characterization of stages is similar to Plotkin's (1969), who describes the early research done by TRW for DOT. He believed that it would take about 10 years to get from stage 2 to stage 3 and another 10 years to attain stages 4 or 5. Plotkin thinks that the only technological difficulties lie in designing the longitudinal controls. Since his review, technology has continued to develop but hasn't been applied to highway automation.

SYSTEM-LEVEL AND POLICY RESEARCH ISSUES

The introduction of automated freeways raises a number of political, social, and economic issues. We identify potential policy problems that apply to all stages of development and others that pertain only to certain stages of system development. We will address the overall problem of building the system in phases in the conclusions section.

Capacity

The first set of issues here pertains to driver preferences for speed. The chief public objective of automation is to increase capacity. One problem that may arise is that because only urban freeways are automated and automated freeways will only be a portion of the average commuter's trip, trip times may not be significantly reduced. Also, travelers may care more about reducing trip time than about capacity increases, and so may purchase equipment and support changes on the roadway's only if they increase speeds or safety. Lenard (1970), however, performed theoretical calculations with optimistic assumptions about sensing and mechanical response rates and points out that automation is probably safer than current conditions only in a speed range of 20–50 mph, and then only with roadside computers (stages 4 and 5). If he is correct, there may be capacity and speed benefits only on freeways where the speeds of nonautomated vehicles are slower than this. This research needs to be updated.

There may not be sufficient gains in service in the early stages of development to win acceptance. It is estimated that route guidance in England could save 5–8% in travel time and distance [Robb (1987), in Kanafani (1987)]. French (1988) reports that savings of about 10% in travel costs could result from route guidance. Totani (1980) estimates a similar savings. These figures will most likely be lower for urban commuting traffic (Kanafani 1987), so the capacity increases and time savings in phase 1 could be small. The Japanese system in Tokyo (CAC) seems to reduce travel times

9-15% (Money 1984) This is not a long-term, equilibrium situation, however. We can expect a reduction in savings as drivers increase VMT due to the lessened congestion. The stage 1 system may not increase capacity much.

When stages 2 and 3 are deployed, urban freeways will be clogged and gaining access to the left lane(s) will be very slow and not worth it for short trips. Automation is thus unlikely to help a great number of drivers in urban areas during these stages. About 60% of trips are 5 mi or less (Stephens et al 1968). A related problem is that in the early years of stage 3 the dedicated lane may be lightly used, which will reduce overall freeway capacity and could cause public concern.

Stages 2 and 3 present other problems because vehicles have lateral and longitudinal controls but do not communicate with the road or each other. Sensational reaction delay (where delays in each vehicle's response is added to each succeeding vehicle's delay) could cause severe flow turbulence and loss of capacity (Glimm and Fenton 1980). For these same reasons, Barmwell (1973) believes that 3,600 vplph is a likely maximum, at 55 mph (current maximum flows are about 2,000). Bender and Fenton (1970) also believe that capacity will be limited, even in stage 5, to less than 3,600 vplph, due to time lags in the servomechanisms in the vehicles and that only the electrification of the roadway will permit closer headways and higher flows by allowing for the simultaneous activation of vehicle braking and engine power changes. Ehas et al. (1977) also believe that capacity will be limited to 3,600 vplph at 60 mph and that higher speeds are not cost-effective, because of increased fuel consumption. It is possible, however, that the roadside computers may be able to coordinate platoons of vehicles and achieve higher flows in the dedicated lanes in stages 4 and 5. This research needs to be updated to account for current technologies.

In stages 2-4, it seems likely that extra lanes will need to be used to allow merging. Our preliminary calculations based on standard vehicle engine (acceleration) and braking performance characteristics, which do not change with automation, show that flow in the automated (left) lane drops below 3,000 v/h if speed differences between it and the merge lane next to it exceed 20 mph (8.94 m/s), due to limitations in merging acceleration rates. Perhaps two merge lanes will be needed, since the speed change will be from, say, 10 mph (4.47 m/s) to 50 mph (22.35 m/s). This will require the dedication of more existing lanes to automated vehicles for merging to get the necessary speeds. That will be difficult, operationally and politically. Plotkin (1969), who worked for TRW, believed that algorithms needed to be developed to manage flows. Sinha et al. (1988) state that these models still need to be developed. Saxton (1980) believes that it may not be feasible to have automatically controlled and manually controlled vehicles on the road together (stage 4).

In stage 5, nonautomated vehicles will have to be kept off the central city (fully automated) freeway segments to keep speeds up. Forcing cars off of the freeway will present operational and political difficulties.

The vehicle mix in all stages will cause speed and headway problems due to differing acceleration and deceleration rates and differing speeds on hills. These differences would decrease capacity in the automated lane(s) and the merge lanes next to them, in stage 4, and in all lanes in stage 5, especially on grades, unless low-performance vehicles are kept out of the automated

lane(s). Acceleration rates below 0.25 ft/sq sec, experienced by trucks, reduce the flow in a 65 mph (24.59 m/s) automated lane to below 8,000 v/h, for example, because large spacings between platoons is needed, to permit trucks to merge in. Low-performance vehicles could be prohibited from some of the automated lanes, but truck and bus operators can be expected to want to participate to a high degree, because of the potentially high economic benefits for them.

Accidents in the automated lanes would presumably take the same time to clear up as they currently do and so would delay more cars per hour in stages 3-5 until traffic can respond to rerouting guidance, because of the higher flows. Also, in the initial period of each stage, there may be more accidents and people could complain about the loss of freeway capacity.

Actual capacity will also be reduced by vehicle reliability problems. Cheney (1976) states that automated vehicles will need to be about 10 times as reliable as current autos for the system to work and that equipment checks at on-ramps will only check operability (at the moment), not reliability. Assuring reliability will be the responsibility of the vehicle owner and such maintenance "cannot reasonably be expected to happen." If accidents increase, capacity gains will be reduced. However, the vehicle's maintenance record could be encoded on a chip that could be sensed by the on-ramp device in stages 4 and 5. We discuss this problem more under "Safety."

In-road sensors or guiding wires will possibly add to repair costs and increase the frequency of road closings, which would reduce capacity.

If automation works and increases flows, off-ramp congestion will worsen and limit freeway capacity. Wachs (1976) states that there must not be delays at the point where vehicles switch from automatic to manual control, in order for the system to appeal to travelers. If offramps are widened, traffic on associated central business district (CBD) arterials will increase. This will result in opposition from residents near some arterials and along alternative surface routes. Residential property values could decline. Parking in the CBD will have to be increased, which is technically possible, but has adverse land-use impact, because it increases distances between other land uses.

When there are accidents, route guidance will direct autos to alternative routes. Congestion on the alternative routes will result unless the routing advice is responsive to this behavior, or predicts it and spreads the traffic around (Gosling 1987). A related problem with regional guidance will occur when snow or rain reduces headways in one part of the metro freeway system and traffic is rerouted. Regional traffic-control programs will have to be able to adjust all flows leading into the areas taking the extra traffic. Models to handle these complex, dynamic allocation demands need to be developed.

It is critical to perform this traffic-capacity research early in the automation program, since the major objective of automation is to increase capacity.

Air Quality and Noise

Automation (as well as new freeway construction) will increase VMT and therefore air pollution and noise. Most major metropolitan areas are air-quality nonattainment areas and so legally may not be able to accept major roadway improvements that result in VMT increases. Nationally, urban auto emissions are forecast to rise after 1990 ("National" 1979, "The Path" 1987).

For example, in the Los Angeles region in 1986, the standards for ozone, CO, fine particulates and NOX were violated and motor vehicles contributed about 60% of all emissions ("The Path" 1987). Emissions there are forecast to fall slightly in the late '80s and early '90s, but rise after that, unless major new controls are adopted on stationary and mobile sources. The region is proposing to encourage cleaner vehicular fuels and require better maintenance of emission-control equipment. Other policies being considered include reductions in the growth of VMT, building rail transit, and parking controls in the central city. Even with all of these measures, it is doubtful that all air quality standards can be met by the year 2000. Many other metropolitan areas will experience this problem. Both the recent southern California and Sacramento metropolitan transportation studies show transit construction as reducing hours of traveler delay and VMT more than freeway building does, and therefore leading to better air quality (*Regional 1988*, Sacramento 1988).

In the future, it may be held to be illegal under the Clean Air Act to expand freeway capacity or build new segments in nonattainment areas, if higher emissions and worse ambient air quality will result. Automation will certainly make attainment more difficult to achieve, regardless of the pollution-control measures that are enacted. The Office of Technology Assessment (*Urban 1988*) estimates that 37 metropolitan regions will not be able to meet the federal ozone standards even after all existing emission (tailpipe) improvements are made, unless the growth in VMT is reduced. California has tougher auto emission standards, so attainment will be more difficult there. Both bills being considered in 1989 as amendments to the Clean Air Act (HR 3054 and S 1894) and a statute recently passed in California (ch 1586, Statutes of 1988) require controls on the growth in VMT in nonattainment areas. Researchers need to compare the air-quality and noise impact of automation with the impact of other measures to reduce congestion, such as improving land-use patterns and instituting parking controls (Shoup 1982).

Noise is a major problem in large cities. Noise increases with vehicle speed, above 20 mph (8.94 m/s) (Salter 1983, Hendriks 1985). A doubling of flows or speed doubles noise generation on the roadway (3 dba) (Meyer and Miller 1984, Bolt Berank and Newman 1976). Thus if automation succeeds in speeding up freeway traffic and increasing VMT on freeways, there is likely to be adverse impact on health and property values. It is possible that such major increases in noise and pollution will motivate cities to seek legislation requiring that state highway departments secure freeway agreements from the affected localities before automation can proceed. Such an outcome would cause problems where freeways traverse high-income communities or where past freeway battles have activated people.

Pollution concerns will certainly become more important in the immediate future. A 1988 national poll showed that 65% of Americans agreed that "protecting the environment is so important that requirements and standards cannot be too high, and continuing environmental improvements must be made regardless of cost" ("New York" 1988). This research should be a high priority, because of the large adverse economic effects of air pollution and noise. Sound walls could help (Elias et al 1977), but they reduce driving comfort and increase noise and pollution levels on the freeway. Electrification of vehicles or the use of hydrogen fuels would also help but are expensive (DeLuchi et al 1987).

Safety and Liability

Another important objective of automation is increased safety. Saxon (1980) reports that human error is a major cause of 71-93% of accidents. About 15-40% are caused by environmental factors and 3-12% are caused by vehicle failure. There appear to be difficulties that need to be examined, however. A fundamental question is whether the technology can be made reliable enough to overcome the risk of higher speeds and closer headways.

First, the roadway presents potential hazards. Snow, ice, rain, and fog could be difficult to handle safely, even if the system slowed vehicles down (Elias et al 1977). Headways can be close only if pavement surfaces have consistent frictional resistance, that is, no patches of water, snow, or ice. Control programs will have to be conservative and have good intelligence regarding road surfaces.

Lightning may cause electronic breakdowns, and so vehicles will have to have graceful failure modes. For example, vehicles should probably go into a "glide" mode when automatic control fails. Also, ice or frost may prevent the transfer of signals to vehicles from roadway computers (Willingham 1976).

Second, drivers may not be able to handle the reaction times. In stages 3 and 4, the merge lane, where vehicles are under manual control before entering, or after leaving, the automated lane may be unsafe. Would drivers get their attention up fast enough, when merging out of the fast lane? What about drivers who are nervous, because of the close headways and make programming mistakes when under automatic control? Shladover (1989) believes that partial automation may be unsafe, because of ambiguities concerning who is in control during the switchovers and during emergencies.

In stages 1-3 on the freeway and in all stages on surface roads, the computer screen in the vehicle will take the driver's attention away from the road. These screens include map displays and textual information (Gosling 1987). The most advanced navigation aid and route-finding system has complex displays and the proponents are considering voice communications, to increase safety (Nakashita et al 1987).

A related issue is driver skills. Illiteracy is currently a safety problem in auto driving. Waller and Hall (1980) report higher accident rates per mile for drivers with poor reading skills, controlling for income. They do not think that improvements in highways or autos can help much and advocate written literacy requirements for driving. This problem will be much worse with reading computer information and programming instructions, both required in order to travel on an automated freeway. Furthermore, there is an equity problem, since illiteracy is correlated with income and race. Waller and Hall (1980) found that the illiterate drivers were disproportionately non-white males.

Third, vehicles must be very reliable. Automated steering and braking systems will have more parts and more failure modes than nonautomated systems. Overall, we will probably have fewer accidents caused by human failure and more caused by mechanical failure. It is unclear if the result would be fewer accidents.

Cheaney (1976) states that automated vehicles will need to be about 10 times as reliable as current autos to be as safe and that a "very expensive" maintenance program will be needed. He believes that such maintenance is doubtful because of the likely inability of vehicle owners to follow a rigorous maintenance program, thus, such a system "is bound for failure." McGean

(1976), states that close-headway vehicles will need to have redundancy in their safety systems in order to be as safe as they are currently. Furthermore, detection devices must enable the driver to know if any systems are not operable while under way. He believes that the maintenance schedules would be similar to those for commercial and private airplanes, where expensive maintenance is required at specific intervals and it is illegal to operate the vehicle if the maintenance is behind schedule. This burden may make it very expensive and tedious to own an automated vehicle. Elias et al. (1977) believe that automated systems must be 20 times safer than the current system in order to be acceptable to the public, because of the driver's loss of direct control of the vehicle. We note that commercial air travel is about 10 times safer than auto travel per passenger-mile and that the public still seems to be much more concerned about deaths from air travel than about deaths from auto travel (because of the large accidents and the involuntary nature of the risk in air travel).

Fourth, there is the problem of public perception. Even if automation were safer, we can expect fewer but larger accidents, due to the close headways (Lenard 1970), which would cause public concern (Elias et al. 1977). If the risk of auto driving is no longer seen as voluntary, but as involuntary, that is, determined by government agencies and private firms, auto travelers are likely to demand much lower accident and injury rates, perhaps similar to those for flying. The fact that the causes of accidents will no longer be known to travelers will reinforce this trend to require much safer systems. Furthermore, drivers of nonautomated vehicles may complain if the automated vehicles cause accidents that clog the freeway. This could arrest the development of automation.

Also, the victims will tend to blame the accidents on the vendors of the devices and on state highway departments. This concern over accidents ties in to the issue of liability. Who is at fault when accidents occur in a system with public components as well as private ones? It seems that automation will not succeed unless liability is limited, which will be politically contentious. Automakers may not participate unless they are indemnified against damages. State highway departments are currently having serious problems with liability claims (Dunham 1987). Apparently, route-guidance systems in the U.S. are already being limited to just presenting maps and not advising on best routes for fear that lawsuits could result from incorrect route descriptions that contribute to accidents.

These safety issues need to be addressed in order for automation to be implemented.

Costs, Benefits, and Equity

Automation presents questions regarding both cost and equity. First, let us examine costs. Costs may be categorized as direct or indirect. The largest costs are likely to be the indirect ones that affect the metro regions and the nation.

Automation needs to be examined from the standpoint of national economic efficiency. This is the standard for highway-project evaluation and is becoming accepted as the standard for evaluating transit funding (Johnston and DeLuchi 1989). In general terms, auto trips are heavily subsidized and also cause large external costs. The subsidies include subsidies to oil and steel, to roads, and to private and public parking. The external costs include

pollution damage to human health, property, crops, forests, and ecosystems, uninsured loss of lives and work days, and congestion created on other modes sharing roadways. These quantifiable costs are quite large, but are overshadowed by the probable external costs of a greenhouse warming.

Automation may not result in cost savings to travelers, because as travel speed or convenience increase, people commute farther (Money 1984). In the past, we have thought this greater VMT to be economically beneficial. Now, it is unclear if the movement of people to commute from suburbs that are farther out is a regional economic benefit, given the external pollution, infrastructure, and subsidy costs. Also, the further spreading of metropolitan areas will increase the disadvantage to lower-income people, who will have to travel farther on average. Especially disadvantaged may be the working poor living in central city ghettos, many of whom counter-commute to suburban jobs.

The economic benefits of the early stages of automation may also not be great, making implementation difficult. The travel savings from route guidance in England are estimated at \$1.2 billion/year [Jeffery (1985), in Kanafani (1987)]. If there are about 18,000,000 autos in England (*World* 1986) and we assume a 10 year payback for the devices, only \$405 can be spent on them, installed (using a 10% discount rate). This sample calculation shows that stage 1 may not be financially beneficial to the driver, which will hinder movement to later stages.

Likewise, when the automated lane is first opened in stage 3, it may be underutilized, which could cause public concern. The diamond lane HOV experiment during the late 1970s in Los Angeles caused an uproar due to the low use rate for the lanes (Wachs 1982).

One economic benefit that needs careful examination is the reduction in time costs that automation may bring. On the one hand, drivers perhaps can read or undertake other tasks while driving on automated lanes. This will reduce time costs. On the other hand, many people cannot read in a moving vehicle and some people would feel anxiety from the loss of control of their vehicle, thus no cost reduction would occur for them. Driver responses to these situations need to be examined.

Automation may permit the automatic tolling of vehicles. Such pricing may not prove to be acceptable, however, because of privacy concerns (Borins 1988). If tolling is not implemented, gas taxes may be the likely source of funds. Automation may be subsidized from state or federal general funds. If subsidized, automation may be seen as taking money away from transit and therefore regressive.

There are also direct costs that should be estimated. Automation will add perhaps \$1,500-\$2,000 directly to the cost of car purchase [Cheaney (1976) estimates \$1,000 in 1972 dollars and Elias et al. (1977) estimate \$1,000-\$2,000]. Such a level of expenditure, required of all vehicle owners at the start of stage 5, would double the cost of a significant portion of the fleet and could deprive some owners of a work vehicle. Those lower-income persons that can still afford a vehicle will have higher total costs per mile caused by the program than wealthier drivers, since they drive fewer miles per year. Poorer persons will also benefit less than wealthier ones, since they have low time costs, and the chief savings is likely to be in the form of time costs. In two-car households, the second car will tend to be eliminated or used just for nonfreeway trips, because of the increase in front-end cost

This change may hurt women and other part-time workers disproportionately.

Maintenance costs will probably be substantially higher, also, to ensure the tenfold greater reliability thought to be required (Cheaney 1976). It is uncertain how much roadway computers and sensors will cost. If gas taxes rise to pay for the public parts of the system, there could be an equity problem, with many drivers paying more operating costs and not having on-board devices. We could tax the on-board computers, but this would raise their cost and slow down their adoption, at least initially.

Certain equity issues need to be addressed. The selection of the specific freeway segments that are to be automated raises equity issues. We may overserve radial commuters, for example, if we automate the freeways leading to CBDs first. This is because congestion in and into central cities may not become much worse and thus not require automation. Central cities have lost population growth share compared to suburbs ever since 1920. In the aggregate, central cities lost 3.7% of their population from 1970 to 1979. Central cities in the north and east also lost an absolute number of jobs, while those in the west and south experienced only a slight gain ($\sim 1\%/yr$). These drops were caused by the increasing use of the automobile and suburbanization of employment, because the phenomenon was experienced in cities of all sizes simultaneously (Heilbrun 1981).

While these population losses have been occurring, radial access capacity has been vastly increased. Concurrent increases in congestion have been primarily caused by the shift from transit to autos (Mills and Hamilton 1984). Moreover, the median real household income, which has not risen since 1967 (Statistical 1987), may not rise much in the future, due to the possibility of a leveling off in productivity. Households may cut back on travel and the proportion of households living in single-family homes in suburbs and exurbs may decline.

If automation is not needed most for radial commuting, it may be needed for commuting between suburbs. If that is the case, we are then giving relatively well-off people better choice of work and residential locations across fairly similar locations, which may be economically inefficient and may be seen as unfair.

There are lesser, but still important, equity issues. Neighborhoods receiving more traffic as a result of automated route guidance will probably experience a drop in residential property values (Gosling 1987) and so political opposition from these landowners, as well as from residents, can be expected (Kanafani 1987).

To summarize, there are major equity issues that arise if we automate freeways. About one-third of adults do not drive and that percentage is slowly rising as the proportion of elderly increases. It may seem inequitable to many people to spend a large amount of public money, even fuel taxes, to improve private transportation. Buses could use the automated lanes, of course, but the funding would be going to automation, not buses.

All of these economic issues need to be investigated, since automation will be expensive and controversial.

Privacy

Stages 4 and 5 require the collection and processing of vehicle-position data by roadway and network computers. The presence of this data, even if

for brief periods, raises privacy questions.

As federal, state, and private data banks proliferate, the public may become more opposed to these easily moved records. The public may not believe transportation agencies when they say they will not keep records of vehicle movements. In the past, telephone records have been used in law enforcement (and still are) and for illegal spying on citizens. Automated monitoring of work stations is now becoming a serious issue, and is access to computerized bank records. Automated radar systems are in use in Germany to catch speeders. License plates are automatically imaged and the speeder is billed for the fine.

Modern automated data systems usually contain more-detailed data than manual systems and the information is more accessible, so there are more security problems (Laudon 1980). Even short-term data pools, such as the type automated highway systems would utilize, would not necessarily be secure. "Inevitably, such data banks will become attractive targets for government agencies, blackmailers, foreign opponents, law enforcement, and perhaps even lawyers in court actions" (Ware 1980). This view is shared by the U.S. Privacy Protection Commission (Technology 1977). "The most significant implication of transaction data captured in machine-readable form stems from the fact that they can be readily utilized for multiple purposes, some of which may be unrelated to the transactions or events that generated them" (Oettinger 1980).

Abuses of privacy by government agencies appear to be an increasing social concern in the U.S. and in other countries (Rule 1980). Similar abuses have occurred in Great Britain (Simons 1982). Many laws have been passed in the U.S. to protect privacy (Sterling 1980) and similar laws have been adopted elsewhere (Simons 1982).

Borins (1988) blames the failed 1985 attempt to implement electronic road pricing in Hong Kong on fears of a tax increase and concerns over privacy. A monthly bill would have been sent to all vehicle owners showing the time and location of every charge. The government maintained that these records were to be kept confidential, but not one of the 19 district advisory boards favored the proposal and it was also opposed by three local computation organizations as being "ethically suspect" and susceptible to unauthorized use of the data. The government has fallen back to a pilot project that will collect electronic tolls in a tunnel on two special lanes that drivers who voluntarily join the program can use. Borins states that privacy concerns are probably stronger in Europe and the U.S. This case study raises serious concerns, since the later stages of automation require vehicle position data to be kept in the roadside computers. Shladover (1989) agrees that dynamic control of vehicles on networks creates a privacy problem. Automation could possibly lead to congestion pricing in the U.S., according to Kanafani (1987), and so the Hong Kong experience may apply for this reason also.

Methods to assure the confidentiality of vehicle movement records, such as encryption and identification on a zonal, rather than network, basis need to be developed early in the system-design process. If vehicles can communicate among themselves in order to control speeds and merging, then the roadside computers may not have to even identify individual vehicles. If the records are used for levying highway user tolls, the security problem is extremely difficult since records will be kept for at least several months. Perhaps charging by zones or selling annual passes for high fees will reduce

this problem Another possible approach would be to have the records kept on the vehicle, in the form of a prepaid computer chip that deducts charges as it passes tolling stations

This issue must be addressed early, as it is a critical one The privacy issue could reduce support for automated highways among those that will be among the first and most direct beneficiaries, the upper class

Public-Private and Local-State Cooperation

Roadway automation will require an unprecedented degree of cooperation on computer standards, vehicles, and freeway components, as well as in the operation of the roadways Since signals and traffic on local and state roads will have to be coordinated, there will be problems working out the ownership and control of signals, beacons, sensors, and other hardware on the local roads and on deciding which agencies have authority over traffic control (Goshling 1987)

The auto industry will need to be indemnified for its investments in manufactured parts if the states do not develop the freeway parts of the systems and the concept fails In general, there are large start-up financing problems that need to be investigated Vehicle owners, of course, will want some assurance that the systems will be completed if they are to invest in on-board equipment

SUMMARY

We have identified a host of research issues important to the development, implementation, and acceptance of freeway automation

It is not clear that capacity can be increased unless offramps and associated arterials are expanded Flow models need to be developed to investigate this critical issue Likewise, the effects of merging and of trucks and buses on hills need to be investigated with such models Special lanes for heavy vehicles and tolling or regulating them to off-peak periods need to be examined in terms of effects on capacity and on economic welfare The importance of accidents in causing congestion needs to be carefully investigated and methods of routing traffic around accident sites need to be developed and tested The effects of higher capacity on off-ramp arterials need to be examined and methods need to be developed for handling these higher loads, such as one-way streets with parking bans and TSM The effects of the early stages of development on capacity and trip times should be estimated in order to see if people will participate Also, we need to investigate ways of screening nonautomated vehicles off the freeways.

Increasing speeds and capacity will result in higher VMT and more air pollution and noise These effects need to be modelled The effects of higher travel speeds on trip-making and on job-location choices also need to be estimated in order to determine the long-term effects on air quality and noise The potential for switching to hydrogen or electric propulsion systems needs to be looked at For sound control, freeway sound walls, quieter engines, and quieter tires should be investigated

It is unclear that safety will improve, due to potential problems with drivers, vehicles, roadways, and weather We need to develop prototype vehicles with dual electronic and mechanical systems and investigate their reliability Also, the use of on-board chips to store the maintenance record needs to be

studied Driver behavior should be measured, initially through simulations and later on test tracks Voice computers should be developed and tested The ability of all economic classes of drivers to handle these systems needs to be looked at Risk perception and liability are related issues that must be examined Liability could be apportioned with statutes and with professional protocols that spell out the role of each manufacturer, the highway agencies, and the drivers On-board black boxes could be used to record system status prior to failure

There are questions regarding economic efficiency that need to be addressed, as well as issues regarding the distribution of economic effects on various income groups and on central city versus suburban residents The ability of lower-income vehicle owners to afford automated vehicles should be examined Equipment and maintenance costs need to be estimated Economic analysis of various methods of paying for the public improvements must be performed Long-range network models can be used to tell us who the beneficiaries are compared to the "do nothing" alternative, where congestion worsens and workers and employers adjust their locations and travel behavior It is important that we try to perform economic-welfare analyses of these major alternatives Last, we need to investigate the economic effects on various classes of drivers in the early stages to see if they can be expected to purchase the equipment

Privacy concerns will be critical, especially if citizens suspect that automated tolling could follow from freeway automation Methods of guaranteeing confidentiality through the suppression of locational data as soon as it is not needed must be developed It may be possible to exempt vehicles that pay a maximum annual fee Another idea that needs to be explored is storing the trip and time data on the vehicle in a chip

Finally, ways of sharing planning and operation responsibilities among public bodies and with the vendors of the vehicles and devices need to be investigated Standard protocols for system design and operation need to be suggested

This is an ambitious research agenda and all of these studies need to be performed before, or together with, the R&D on the technologies Many of the possible problems arise in the early stages of development and so implementation needs to be carefully analyzed

Implementation

The best path for developing the system needs to be investigated Saxton (1980) believes that incremental implementation is the biggest problem for automation Orski (1976) also believes that a crucial challenge for automated systems is that they must be built in segments to be politically acceptable The staged development of automated systems that we have outlined here is built in segments over time, but there are potential problems in all of the stages Stage 1 may not be efficient for drivers because of the small time and operation savings Stage 2 will likely not be efficient for the owner because of the small increases in safety and speed Stage 3 may not be efficient for drivers and may cause public concern in the early years if the dedicated lanes are used Even stage 4 may not be efficient for the owner, due to merging and vehicle-mix problems Stage 5 may be efficient for a few years until congestion catches up, but requires that all vehicle owners purchase expensive equipment Shladover (1989) states that it may be very

difficult to make the early stages of automation economically efficient, because of their small scale and limited effects

There are equity problems at each stage also To be implemented, freeway automation, since it relies on private investment so heavily, must pass both public and private efficiency and equity tests at each step It must also pass the test of political will at each stage This is a difficult set of hurdles

On the other hand, there may be pathways that are efficient, are politically acceptable, and attain the freeway improvements before large numbers of vehicle owners have to purchase devices De Marco (1976), for example, suggests an evolution from dial-a-ride bus to bus-priority signal control to priority freeway access to dedicated freeway-bus lanes to automated bus guideways Since buses are publically owned and operate in defined areas, such an evolution may be politically feasible, if we replace the guideways with dedicated freeway lanes This pathway would lead to the automation of freeway lanes that private vehicles could then use, allowing for a way out of the investment (chicken-and-egg) dilemma Such pathway analyses needs to be performed

Finally, we need to ask if we are asking the right question by seeking to add to the supply of roadway services to relieve congestion Altshuler (1979) believes that congestion is not a problem for American transportation He believes that the real issues are high energy consumption, air pollution, fatalities and injuries, and equity for the transportation disadvantaged He shows that both freeways and transit tend to serve suburban commuters and do not relieve congestion, even in the short term Furthermore, he shows that these improvements do not improve safety, air quality, or energy efficiency This debate points to the need for a basic examination of urban planning and transportation alternatives at the same time that we explore automation technology

CONCLUDING COMMENTS

Before funds are spent on major transportation improvements of any kind, analysts and decision makers need to decide if congestion is really a problem and, if so, whether to just meet demand or to also constrain it Energy policy in the U S now encompasses conservation (demand reduction), and water-resources allocation likewise is beginning to include conservation Pollution controls are beginning to bring about the recycling of industrial feedstock materials Concerns over urban air pollution, acid rain, and CO₂ will likely result in more expensive controls on vehicles, higher fuel taxes, and auto disincentive programs We should examine demand-management alternatives that are complementary to automation, such as roadway tolls and full-cost pricing of parking and fuels in order to utilize the existing roadways most efficiently, whether automated or not Urban economists believe that central-city congestion is not inefficient, but reflects the efficient combination of costs for traveler's time and relatively expensive land (Mills and Hamilton 1984)

Perhaps the most interesting problem resulting from automation would be the possible loss of freedom of movement Auto travel is attractive because of the freedom of route choice and time of movement Full automation could lead to freeway allocation through a computerized reservation system Such a system would result in the inability to choose your time of freeway entry

and often in not being able to exit on a desired off-ramp Drivers would also lose control over steering and speed and this may cause anxiety in some people (Elias et al 1977) Moreover, if tolling is used, drivers' movements may be recorded in data banks that could possibly be used by law-enforcement agencies and other groups to monitor their activities Ironically, automation may lead to reduced freedoms

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BUSINESS VIEW OF SMART VEHICLE-HIGHWAY CONTROL SYSTEMS^a

By Albert J. Sobey^b

(Reviewed by the Urban Transportation Division)

ABSTRACT Nontechnical concerns must be overcome before investors will give serious consideration to the large expenditures required for the development of smart vehicle-highway control systems. The most important step would be the development of joint public-private initiatives to create incentives for the U S industry to actively pursue research and development of these (and other) socially beneficial products. Fortunately, there is increasing evidence that these concerns will be addressed and that in due time the nation will be able to take advantage of smart vehicle-highway systems.

INTRODUCTION

This paper has been prepared to describe the business viewpoint on the opportunities for the development and sale of smart car-and-highway systems. Assuming that all of the benefits that have been projected about advanced transportation control systems in this meeting are correct, that will not insure that they will be developed and made available to the using public. The underlying questions include

- Why would a company invest in the formation of a business to produce the equipment or provide the services?
- Why would government officials purchase the equipment?
- Why would anyone purchase the equipment for his car?

SUMMARY

The need for the services that smart vehicle-highway systems can provide has been shown to be significant. They can help improve transportation in and between large cities. The potential benefits include reductions in travel time and cost, reductions in the use of fuel, improved air quality, and lives saved.

The technology is not yet mature, so the technical and economic feasibility of individual systems cannot be addressed with confidence. Many of the technical concepts would not be possible without recent developments in computer and control systems. Cost estimates, which are attractive today, should tend to decrease as engineers find ways to take advantage of advances

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