Title
Time Benefits of New Transportation Technologies: The Case of Highway Automation

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SUMMARY

This paper examines the role of travel time in the choice of transportation technologies. First, the components of travel time are introduced and compared among alternative modes. Next, a series of highway automation concepts is created, and the time benefits of each are discussed. Finally, the effects of automation on highway performance are modeled and evaluated, first looking at the space efficiency of highways, then measuring the benefits of increased capacity and increased velocity.

The paper demonstrates that even simple forms of highway automation can provide important travel time benefits. Automated low-speed and stationary merging can reduce queueing at the entrances to bridges, tunnels and other bottlenecks. And “mini- highways” can reduce delays crossing urbanized areas.

Highway automation may achieve great benefits within a few niche markets. But these markets are likely in congested existing cities -- where construction of new conventional highways is all but prohibited -- rather than radically transformed “cities of the future.”

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CHAPTER 1 INTRODUCTION

The quest for mobility is age old. Whether in 19th century England during the advent of the steam train or 20th century America at the introduction of jet aircraft, the drive to overcome distance faster, more safely and at less cost has been with us. But as we head toward the 21st century, concern has risen that our mobility is on the verge of decline. Crowding in cities and in the airways has led to increased delays for travelers, and deterioration of the infrastructure has caused accidents and forced road closures. To address the concern of reduced mobility, this paper investigates the question of how new technology -- highway automation in particular -- can allow us to reduce travel time in the future.

Over the last 50 years, a tremendous literature has evolved on highway automation. Much of this literature is almost utopian in spirit, with new transportation systems predicated on the transformation of cities (for example, see Canty et al, 1968; Curry, et al, 1977; Pell, 1966; U.S.H.U.D., 1968; Wolf, 1967). Other literature is more pragmatic, with the engineering aspects of automation being the focus (e.g., Barwell, 1983; Bidwell, 1965; Black, 1975; Fenton, 1977). What seems to be lacking in the literature is a notion of how the engineering advancements can be directed toward solving specific problems in cities.

History tells us that new modes of transportation seldom supplant their predecessors. 150 years after the first trains, we still transport enormous quantities of goods by barge and ship. 80 years after the first automobiles and trucks, we still rely on trains for moving commuters and bulk commodities. And 40 years after the first jet aircraft we still use automobiles for most of our personal travel. When automation comes to pass, its initial form will probably be far from the utopian vision of new cities designed around fast moving road networks. Instead, automation will likely exist in just a few places, each in a simplified form, perhaps just connecting one point to another. Within this context, the question to answer is: in the near future, what transportation niche can highway automation serve?

The paper begins with an examination of the role of travel time in technological choice. Next, the focus turns to highway automation. A hierarchy of automation schemes is created, and the time benefits of each are discussed. Finally, the effects of automation on highway performance are modeled and evaluated, first looking at the space efficiency of highways, then measuring the benefits of increased capacity and increased velocity.

CHAPTER 2 ELEMENTS OF TIME

New transportation technologies affect the costs and benefits of travel. Foremost, technology affects the time required to overcome distance. But technology also affects the way we experience time. Stress, safety, comfort -- and the degree to which other activities (such as reading) can be performed en route -- all depend on the mode of travel. Though all are important, studies of traveler route and mode choice behavior suggest that people put the highest weight on time itself (Bamford and Read, 1990; Hensher, 1976). Hence, time benefits of new technologies is the theme for this paper.

Time benefits can be classified according to whether they accrue internally or externally. An internal *benefit* occurs during the trip, sometime between time of departure and time of arrival. *External benefits* occur either before or after the trip. Enhancement of transportation reliability, for example, may increase the likelihood that travelers arrive at work on time. This permits people to reduce the safety margin allowed in their departure time (an external benefit to the individual).

Table 1 lists basic external benefits. On one side, new technology can open opportunities, enabling individuals to travel at different times, to and from different places and with different frequency. On the other, new technology can reduce allowances, either in the form of safety margin or schedule delay (a product of the lack of synchronization between transportation schedules and personal schedules).

Internal benefits accrue during the trip. In an ideal world, every trip would be at top speed, on the fastest mode available, via a straight-line path. The reality is that travel of this kind is far too costly for us to afford. Fast modes of travel demand considerable investment, which can only

Table 1. External Benefits of New Technologies

Enhanced Opportunities for Travel

Type	Example
Time of travel	Freedom to travel at all times of day
Destination of travel	Opportunities to: Work at new job site Shop at different stores Visit more distant friends
Origin of travel	Ability to move to new home Possibilities for new trip chaining
Frequency of travel	Potential to shop or recreate more frequently
Reduced Allowances	
Schedule Delay	Buses scheduled to arrive at work at optimal times Congestion is reduced, so that travelers do not have to avoid peak periods
Safety Margin	Accident prevention reduces requirement for safety margin

be justified when shared over a large number of trips. This sharing -- or consolidation -- process induces delay.

Trip time depends on three factors, length of the trip, time required for changing modes, and the speed of travel on the mode(s). Hence, the three ways to reduce travel time are to reduce (1) circuity, (2) transfer delay, or (3) en route delay (Table 2).

Principally, *circuity* occurs when the guideway is indirect, when routes are indirect, or when longer routes are less costly or quicker than shorter routes (as when airplanes and ships detour to exploit air or ocean currents, or when autos detour to travel by freeway). Circuity is reduced when more routes and guideways are provided, but also when the structure of the route and guideway network is improved.

Transfer delay can be due to schedules, congestion or intermediate transportation. Schedule delay occurs when arriving and departing vehicles are not synchronized, forcing a wait. Congestion delay represents interference between travelers as they compete for shared resources. Queues at turnstiles, bus and train doors and freeway entrance ramps fall in this category . Intermediate delay represents a connection time -- the time spent walking between modes or, perhaps, the time driving through an interchange.

En route delay depends on the performance of the mode and guideway, or depends on congestion. The velocity and acceleration limits of a mode reflect both driver and vehicle capabilities. To ensure safe travel, guideways can further limit performance. Because part of the trip invariably occurs on foot (even if from parked car to office) , human performance is also a factor in travel time. En route, congestion delays can occur when travel paths coincide, as in freeway delays, or when paths intersect, as at traffic

Table 2. Internal Benefits of New Technologies

Type	Example
	CIRCUITY
Guideway	Roadways and railroad located near to trip generators New roadways and tracks constructed
Route	Bus lines routed near to trip generators Bus routes added to serve more areas
cost	Airline and ship routed to exploit currents Drivers select routes that take advantage of fast roads
	TRANSFER
Schedule	Feeder busses synchronized with train departures More train runs scheduled
Congestion	More turnstiles reduce queue at entrance to subway station
Intermediate	Automated walkways reduce connection time
	EN ROUTE
Performance limits	
a) guideway	Roads redesigned to increase speed limits
b) vehicular	Power and braking improved to increase acceleration and deceleration of trains Power and stability enhanced to raise velocity of light-rail vehicles Walking distance reduced to increase average velocity
Congestion	
a) Coinciding paths	Highway capacity increased to reduce congestion delays New scheduling system reduces train delays
b) Stopping	Express trains added to reduce delays for picking up and dropping off passengers
c) Intersecting paths	Computer signalization reduces cross traffic delays at intersections

signals. When a train or bus picks up or drops off passengers, it also encounters a form of congestion delay called a stopping delay.

Technology and Time

Technological capability and technological reality are not the same. The transportation system of today is as much the consequence of economic tradeoffs -- between investment cost and delay -- as it is a consequence of technology. We are not able to travel at the fastest speed via straight-line paths, not because it is technologically impossible but because it is too costly to do so.

According to Pisarski (1987) the average speed of travel for automobile commuters is just 29 miles per hour in the United States. Once circuity is factored in, the average speed, relative to the straight-line distance, would be only about 25 miles per hour. More striking, the average speed of travel by bus is just 13 miles per hour. Even in a modern transit system like BART, the average speed of travel for a typical trip -- Walnut Creek to San Francisco -- is only 36 miles per hour counting station stops. But once access and transfer time are counted, the rate drops to about 20 miles per hour.

Clearly, any new technology must be measured on the scale of total travel time. Within this context, the most important technologies may do nothing to increase peak vehicle velocity. Instead, their benefit may come in changing the economic equation that defines the technological reality.

CHAPTER 3 HIGHWAY AUTOMATION AS A VISIONARY TECHNOLOGY

The technology of transportation includes vehicles, guideways and terminals, as well as the mechanisms that control their operation. Each of these components can act in a “shared mode” (shared among multiple travelers) or a dedicated mode, for the exclusive use of one traveler. From a systems perspective, it is most important to divide technologies along the lines of shared/not shared guideway and shared/not shared vehicle. Hence, Table 3 classifies technologies into (1) dedicated transportation, (2) shared guideway, (3) shared vehicle, and (4) shared vehicle and guideway.

In dedicated transportation, movement is free of the confines of guideway and free of interference with other travelers. It is the ultimate technological vision, one that is only a near-reality for the very few who own helicopters or airplanes. Instead, most travel by Americans occurs by personal automobiles over shared roads and highways, a form of travel that has remained nearly static over the last decades.

The 1939 New York World’s Fair "Futurama" exhibit presented the first vision of a radically new form of shared guideway transportation -- the automated highway. The concept combined the convenience and privacy of the automobile with the relaxation of “chauffeured driving.’ The concept also had the potential for enhanced highway performance, in the forms of increased speed, capacity and reliability. In the late 50s and early 60s, the engineering aspects of automated highways attracted intense research at General Motors Corporation, and later at such places as General Electric and Ohio State University (Barwell, 1983; Bidwell, 1965; Black, 1975; Fenton, 1977; General Electric, 1968; Spreitzer, 1990).

Over this period, four basic versions of automated shared guideway transportation evolved (Barton- Aschman, 1968, lists examples from that period)

Table 3. Transportation Technologies

	The Present	The Future?
Dedicated	Helicopters VTOL Private aircraft	Flying automobile Human flight? Molecular transporter?
Shared Guideway	Automobiles Bicycles Motorcycles	Automated Highways Personal Rapid Transit
Shared Vehicle	Airplanes Ships Hovercraft	Orbiting aircraft
Shared Vehicle and Guideway	Trains on rails Buses	Magnetic Levitation

Automated Highway Ordinary vehicles that come under automatic control when operated on special guideways

Dual-Mode: Specialized vehicles that can either operate on ordinary city streets or on a tracked automated guideway (e.g., the "Urbmobile", Wolf, 1967)

Personal-Rapid-Transit Standardized vehicles operated over an extensive network of automated guideways (see USDHUD, 1968, for example).

Palletized System A system where ordinary vehicles are loaded onto trains, conveyors or pallet cars for long-haul transport (see Canty, et al, 1968; the RRollway system described in Pell, 1966; and the "Magnaline" overhead suspension system in Wolf, 1967). This vision is close to reality, as evidenced by the planned system for moving autos through the English Channel Tunnel.

All of these are designed to provide convenience, privacy and “chauffeured driving,” along with some form of efficiency in long-haul transportation. In the case of PRT, vehicles are standardized and owned by the operating authority, not the individual. This provides economies in the form of reduced parking and fleet requirements. Otherwise, private vehicle ownership is retained.

Today a new wave of interest in guideway automat ion has begun under the umbrella of Intelligent-Vehicle-Highway-Systems (IVHS; see Koltnow, 1989; Mobility 2000, 1990; U.S.D.O.T., 1990). Unlike some earlier programs, IVHS incorporates a wide range of technological improvements, ranging from improved signalization to full-scale automation. Nevertheless, increases in the speed and reliability of computers, and improvements in sensor technologies, have moved the original vision of automated highways closer to reality.

To put highway automation in context, Table 4 compares the time benefits of alternative technologies relative to a base case of single-occupant automobile trips over existing road networks. From this travel time perspective, the benefits of automated highways are little different from the

Table 4. Time Benefits of Technologies

Comparison Relative to **Single-occupant** Automobile Trips
Over Existing Roadway Network
+ improvement; – detriment; ? uncertain

	Circuity			Transfer			En Route			External		
	Guideway	**Route**	**Cost**	**Schedul**	**Congesten**	**Intermed**	**Perfrmnc**	**Congestn**	**Stopping**	**Opprtnty**	**Schedule**	**SafetyMg**
Carpools on Exclusive lanes		–	–	–			†	+	–*	?	– –	?
Express Busses on Exclusive Lanes		–	–	–	?	-#	†	+	–	?	–	?
Lightrail	–	–	–	–	?	-#	–†	+	–	?	–	?
Rapid Transit	–	–	–	–	?	-#	+†	+	–	?	–	?
Convent ional Highways (exstng routes)								+		+	+	+
Convent ional Highways (new rout es)	+		+					+		+	+	+
Automated Highways (exstng routes)					?	–	?	+		+	+	+
Automated Highways (new rout es)	+		+		?	–	?	+		+	+	+

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* Time will increase if driver picks up passengers, but not if passengers meet in central location.
# Time will increase if trip requires transfer
† If technology reduces distance walking from parking lot, further improvements are possible.

benefits of new conventional highways. The key differences are that automated highways can potentially operate at higher speeds. But this gain may be offset by delays associated with transferring from manual to automated roads. On balance, the time benefits of automation may be small in places where new conventional highways can be constructed.

There are, of course, many places where economic or political constraints prevent manual highways from being constructed or expanded. In these cases mass transit and carpools are competitors to highway automation. On one hand, these shared vehicle forms of transportation suffer from added circuity, schedule delay and stopping delay. On the other, they do not demand parking space in the city center, they offer operating cost efficiency, and they do not require new technology.

Overall, the initial niche for highway automation is likely in populous cities where expansion opportunities for conventional highways are limited, and where employment is dispersed. With this in mind, the following presents a hierarchy of automat ion. Each level demands a different degree of technological sophistication and, likely, a different degree of investment.

CHAPTER 4 A HIERARCHY OF HIGHWAY AUTOMATION

Automation can effect improvements in highway performance through control of the longitudinal (in direction of travel) and lateral positioning of vehicles. Control occurs in two spheres: in the forward movement of vehicles within a lane of traffic, and in the merging and splitting of traffic lanes.

A. Automation Without Merging and Splitting of Lanes

Without a capability for automated merging and splitting, the capacity of an automated lane is limited by the capacity of the manual lanes that precede and follow it. This rules out significant gains in lane capacity, but does not rule out other benefits.

Lane Width Reduction Under effective lateral control, lane width could be reduced without sacrificing safety. As shown in Figure 1, the lateral positions of vehicles are gradually adjusted until they track the center of their lanes. Once in posit ion, lane width is reduced and lateral position is maintained by automatic control.

Velocity Increase With lateral and longitudinal control, velocity could be increased while maintaining capacity and safety. Vehicle speed and mean distance separation are gradually increased during a transition phase until reaching an automated cruise velocity.

B. Automation with Merging and Splitting of Lanes

Automated merging and splitting offers the potential for greatly increased lane capacity. However, to gain the benefit of increased capacity, it is not essential to merge and split traffic at high speeds.

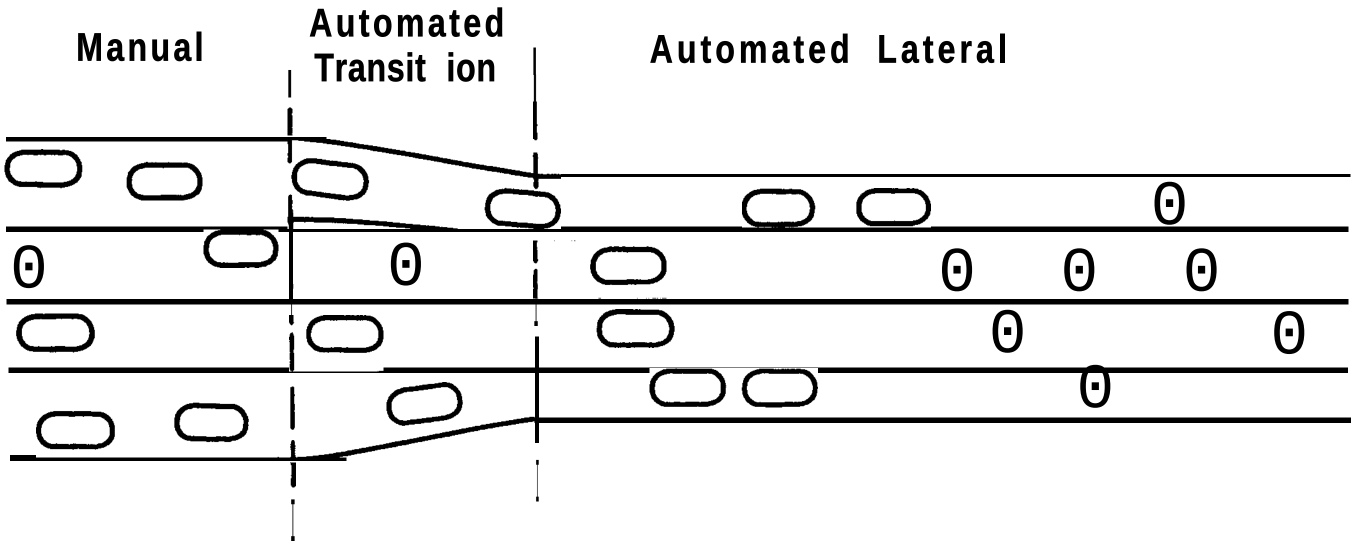

Figure 1. Lane width is reduced through automated lateral control.

Merging from Stationary Position Figure 2 resembles a railroad classification yard. At the entrance to the automated highway, vehicles form platoons by parking in separate lanes. When a lane is filled, its vehicles are accelerated in unison and switched onto the automated lane. The lanes of parked cars are alternately served.

Low-Speed Merge Figure 3 illustrates the concept. As vehicles enter a transition phase, they come under lateral and longitudinal control. To prevent collision, vehicles are staggered appropriately. Once the lanes are merged, vehicles may be accelerated (increasing velocity and decreasing spacing) or, perhaps, grouped into platoons.

High-Speed Merge The most advanced form of automation -- and the form that has attracted the most research -- would allow multiple lanes of traffic to merge and split at high speed, as in an ordinary highway. The benefit of automation is that vehicles could merge and travel within a shorter separation than normal, allowing lanes to operate at increased volumes. Concepts for high-speed merge within a network (such as "synchronous moving-cell control" and platoon control) can be found in a variety of articles, including Fenton (1977), Rumsey and Powner (1974), Stefanek (1972), Tobin (1977) and Varaiya and Shladover (1991).

C. System Scenarios

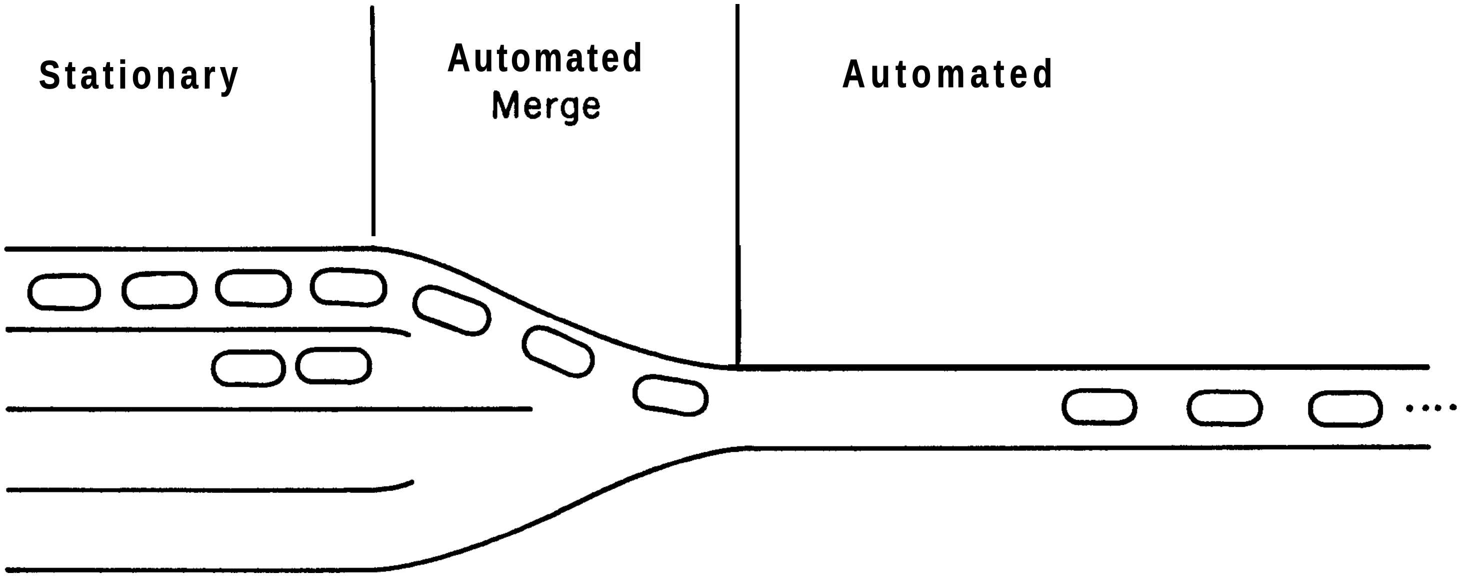

Figure 2. Lanes are merged from a stationary position automatically, to increase lane capacity.

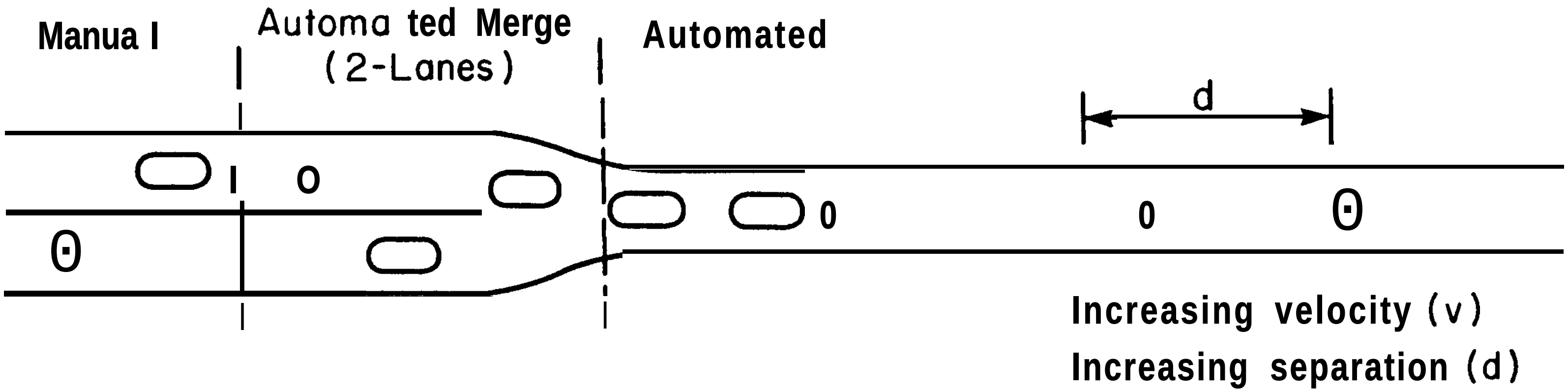

Figure 3. Automated low-speed merge increases lane capacity.

Table 5. Highway Automation Concepts

Scenario 1: Mini-highway

•I High-capacity roadway with 1 or 2 lanes in each direction fit into the space of an ordinary city street (perhaps with cross traffic). Velocity control keeps noise at tolerable levels, which reduces the need for surrounding buffer.

Time Benefits: Reduced circuity and congestion delay.
Potential Application: Highway 101 through San Francisco

Scenario 2: Bottleneck bridge

•I Highway capacity in a narrow and restricted corridor is increased through automated lanes.

Time Benefit: Reduced congestion
Potential Application: The San Francisco-Oakland Bay Bridge

Scenario 3: High- speed Highway

❑ Automation is added to a long-distance/heavily traveled highway. Lane capacity is maintained while velocity is increased.

Time Benefit: Increased peak velocity.
Potential Application: I-5 from San Francisco to Los Angeles

Scenario 4: Express Highway

❑ Automation is provided for commuters traveling long distances to a work center. Lane capacity is increased while velocity is maintained.

Time Benefit: Reduced congestion
Potential Application: Santa Monica Freeway heading toward Downtown L.A.

Scenario 5: Automated Corridor

•I A heavily traveled highway is automated to increase capacity and reduce congestion.

Time Benefits: Reduced congestion
Potential Application: The San Diego Freeway in Los Angeles

Even if high-speed merging turns out to be a distant technology, highway automation can still provide important benefits. If automation is used as a "bottleneck bridge" (to serve a tunnel or bridge, for instance) and queueing is reduced, then the delay inherent to low- speed or stationary merging would be tolerable. Automation could also be less expensive than building a new structure. The mini- highway (Figure 4), express highway (Figure 5) and high-speed highway could also be operated with low-speed merge or stationary merging, either because congestion is reduced or peak velocity is increased.

The mini-highway merits particular attention, given the difficulties of older urban centers -- such as New York, San Francisco and Chicago -- in accommodating automobile traffic. If automation can facilitate smooth traffic flow at low velocity, then highways might become more acceptable for two reasons : highways would not have to be as massive, and highways would not be as noisy. The noise emitted by a typical automobile at 50 feet, in dBA, is approximately (Bolt, et al, 1973):

Speed (mph)	30	40	50	60	70
Noise (dBA)	60	64	67	69	71

According to Llewelyn et al (1971), an increase in noise level of 3 dBA roughly doubles the perceived noise to humans. Hence, a reduction in velocity from 60 mph to 30 mph would reduce perceived noise by about a factor of eight.

The principal use of high-speed merging is in congested urban corridors with significant on- and- off movement (the "automated corridor"). Low- speed merging would have limited value in such places. It would be unrealistic for vehicles to slow each time a new traffic stream merges or splits.

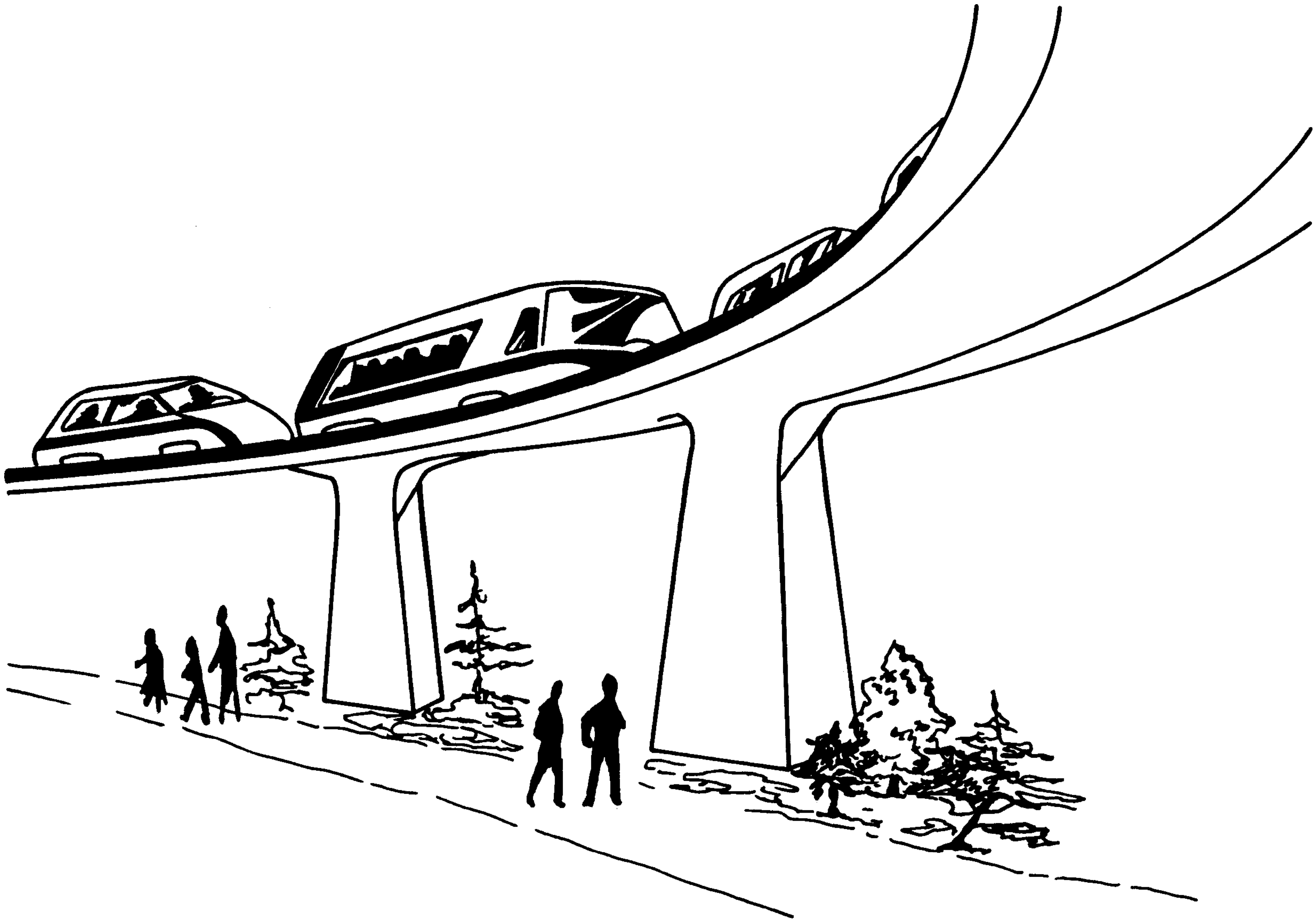

Figure 4. Automated mini-highway provides high-capacity road in urbanized area.

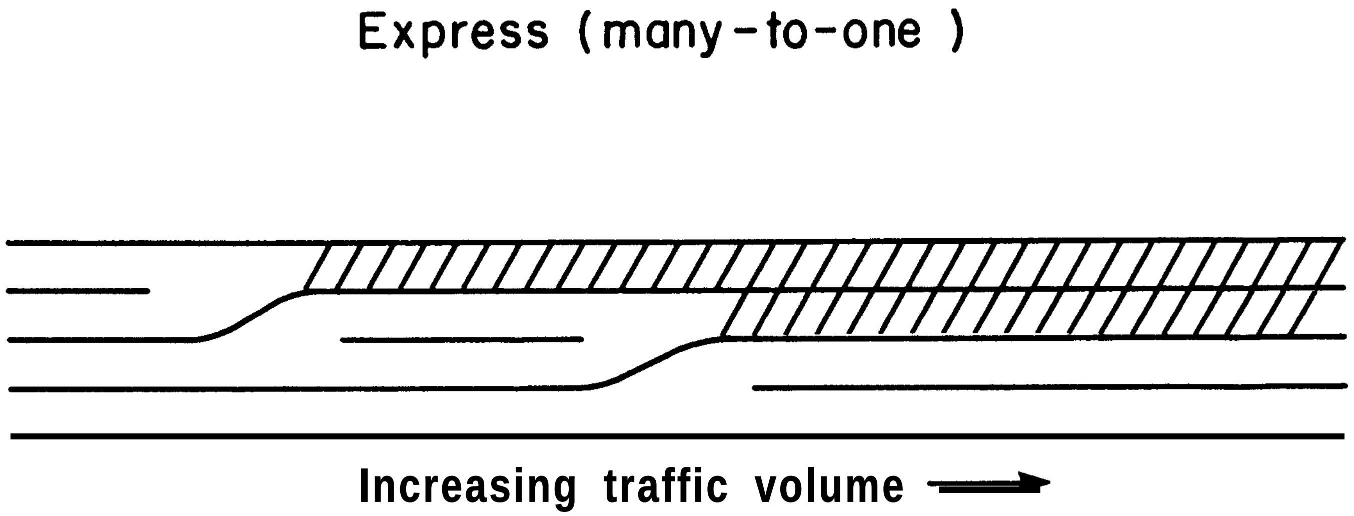

Figure 5. Express highway provides increasing capacity as work center is approached.

CHAPTER 5 SPACE CONSUMPTION

As stated earlier, new technologies are capable of changing the economics of transportation. In this respect, highway automation has the potential for reducing the cost of adding highway capacity by reducing space consumption. To serve a given traffic pattern, space consumption depends on two factors: the capacity per lane of traffic, and the space occupied per lane. Increasing the first or reducing the second can reduce construction costs or allow highways to be built where they otherwise would not fit. (Space consumption also depends on the size of interchanges, but automation is less likely to produce gains here.)

As argued in Meyer, Kain and Wohl (1965), the amount of space consumed by highways is a small percentage of the total automobile space.

> "... local access requirements account for nearly all transportation land uses in urban areas and for about 20 to 24 per cent of total urban land use. To augment this basic highway system with arterials a half-mile intervals would require only 1 per cent more land; and to superimpose expressways on the arterial system at 4-mile intervals would require only another 3 per cent . . ." (p. 311)

They go on to state:

> "... no significant over-all reduction in land-use requirements would result from the large-scale development of mass transit systems for downtown-oriented travel movement except to the extent that such systems eliminate substantial quantities of parking requirements." (p. 311)

The following will examine the reasons why highways do not occupy a larger percentage of land area in urban areas.

A. Capacity per Lane

The capacity of a lane of traffic can be expressed as:

C = capacity per lane

$$= 1000(v/d) \, . \qquad (1)$$

where :

v = vehicle velocity (km/hr)

d = mean separation between vehicles (meters) .

Different combinations of v and d can achieve the same capacity. According to the Highway Capacity Manual (TRB, 1985) a state-of- the-art freeway lane operating at saturation can achieve a capacity of about 2000 vehicles per hour with a velocity of 50 km/hr and a mean separation of 25 meters, (about 5 car lengths) . An automated freeway could increase the capacity by altering the relationship between speed and volume (Beji, 1987; Karaaslan et al, 1990; Fenton and Chu, 1977). As shown in Figure 6, capacity could be doubled by doubling the velocity while maintaining the same separation. Capacity could also be increased at *reduced* velocity, such as a velocity of 40 km/hr with a separation of just 10 meters (2 - 3 car lengths).

B. Space Occupied per Lane

The width of a highway depends on the number of lanes, the lane widths, and the amount of space provided for shoulders, median and surrounding border. This total width varies widely, depending on land values, date of construction and encroaching land uses. The San Francisco-Oakland Bay Bridge, for instance, is just 59 feet wide, but provides two 5-lane decks of traffic. At another extreme, the right-of-way for 8 lanes of rural highway is sometimes as

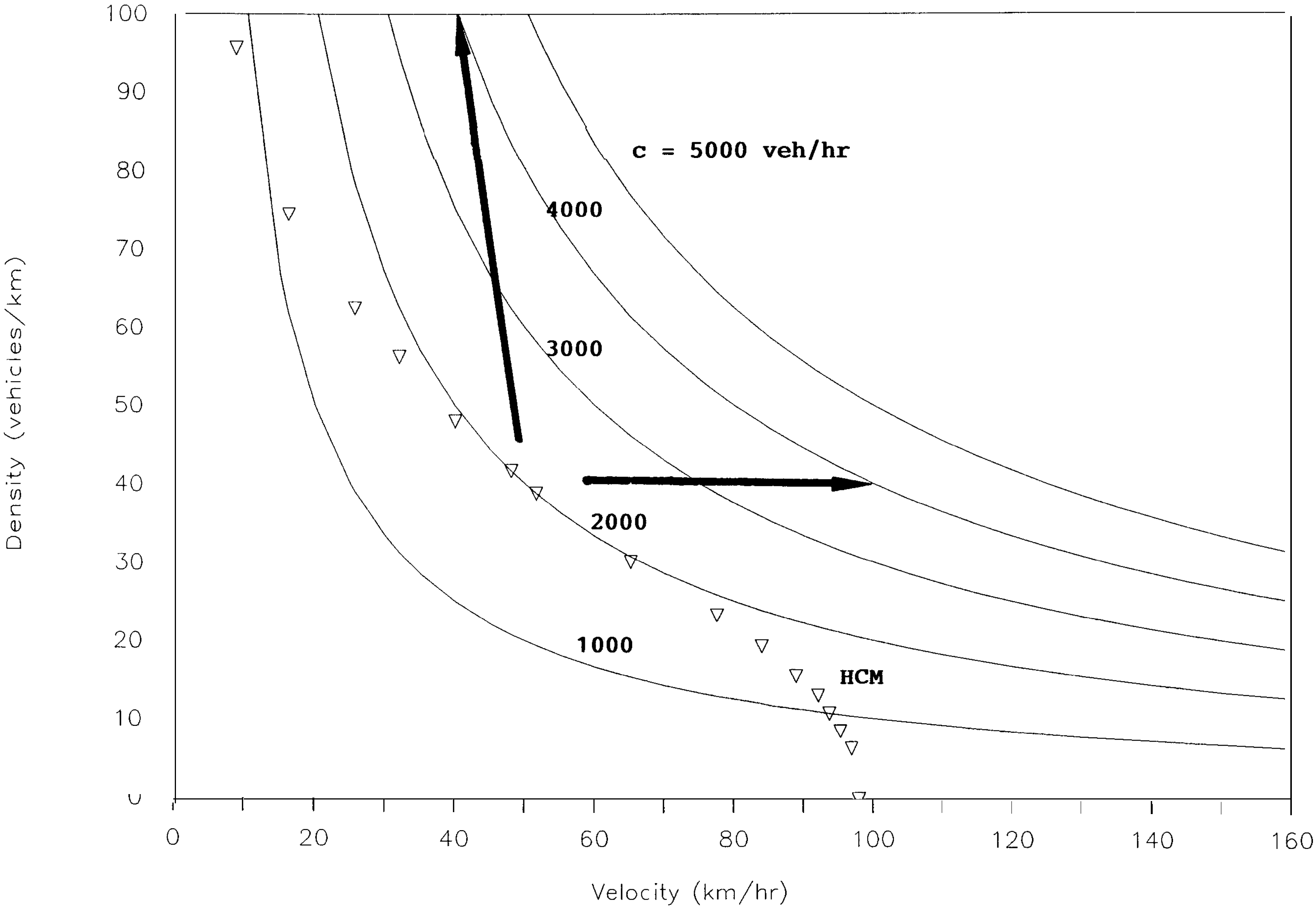

Figure 6. Contour lines show combinations of velocity and density that produce identical lane capacity. Triangles are taken from the Highway Capacity Manual (70 mph)

large as 500 feet wide. According to the ITE Handbook (Homburger, 1982), accepted practice is to provide:

Lane Width	Median	Shoulder Left	Shoulder Right	Border	Total (8 lanes)
12'	16-36'	6'	10'	30-60'	204'-284'

An automated highway has *potential* for reducing the overall width of a highway in four ways:

- ❑ Through longitudinal control: increased lane flow can reduce the number of lanes required.
- ❑ Through control of lateral movement: medians and lanes can be reduced in width.
- ❑ Through *reduced* velocity (and noise): the surrounding border can be reduced.
- ❑ Through increased reliability: the need for shoulders can be reduced.

The last two benefits are speculative. The border and shoulders may still be needed for aesthetics, parking of disabled vehicles or political reasons.

If automation only enables the number of lanes to be reduced -- for instance, from eight to four 12-foot lanes with no change in median, border or shoulders -- the design standard for the right-of- way can be reduced by no more than 23%. In reality, many highways -- especially in urban areas -- are not nearly as wide as suggested by the ITE Handbook. In extreme cases, shoulders, buffer and median have been virtually removed. In these special instances, automation may be the only way to increase highway vehicle capacity. These extreme cases are where automation is most attractive.

C. Regional Land Consumption

The total space occupied by highways depends on demand patterns and vehicle occupancy, as well as space-efficiency. As a point of illustration, suppose that the highway capacity entering a region is sufficient to accommodate the peak period of travel. Let:

N = number of people entering region in peak period

Θ = average vehicle occupancy

t_p = length of peak period

$w(\ell)$ = avera g highway width per lane (accounting for full highway width) if each highway has ℓ lanes.

Then the total width of highways entering the region, S_f, amounts to:

$$Sh = [(\text{traffic volume/hour})/(\text{lane capacity/hour})] \,.\, (\text{lane width})$$

$$= \frac{(N/ot_p)}{(v/d)}\, w(l) \,. \qquad (2)$$

Eq. 2 suggests how to reduce total space consumption:

❑ ☎🗁✆ Reduce total number of trips; (2) Increase vehicle occupancy, or (3) Spread the trips over a longer peak period

❑ ☎🗁✆ Increase velocity; (2) Decrease vehicle separation, or (3) Decrease width per lane.

The last three factors are consequences of the transportation technology, while the first three are products of traveler behavior, which, of course, is influenced by the technology. A technological improvement might entail highway automation, or it might be as simple as substituting one-way for two-way streets, improving signalization, constructing new freeways, or adding sound-walls while reducing buffer. To achieve changes in traveler behavior, roadway prices might be contemplated. In particular, peak-period pricing might induce travelers to avoid travel, or to travel during the off-peak.

D. Space Consumed around a Work Center

In the morning, the predominant direction of travel is toward work centers, whereas in the evening, the predominant direction is away. If N represents the number of person trips entering the center during the peak, then (in the absence of reversible lanes) $2 \cdot S_f$ defines the minimum highway width that must be provided to accommodate the commuters.

Suppose that the work center can be approximated by a circle with radius r. As a proportion of the circle's circumference, highways occupy a space of:

$P_h(r)$ = proportion of circumference needed for highways, city size r

$$= 2 \cdot \frac{(N/ot_p)}{(v/d)} \cdot w(\ell) \cdot \frac{1}{2\pi r} = \frac{Ndw(\ell)}{ot_p var} . \qquad (3)$$

Eq. 3 indicates that the space occupied by highways is most critical when a large number of jobs (N) is concentrated in a center of small size (r).

E. Highway Space in Perspective

There are two distinct tactics for reducing the space consumed by automobiles: reduce the space occupied by moving vehicles, or reduce the space occupied by parked vehicles. The space needed for moving vehicles includes space for highways as well as local streets. Though local streets tend to be the dominant factor, space requirements are more a function of city block and lot sizes than traffic flows. Space for parking and highways, on the other hand, are both very much a function of traffic flow. It is worthwhile to compare them.

The parking space needed to accommodate N employees who arrive during the peak equals (additional parking will be needed for people who travel to the work center outside of the peak):

$$S_p = [N/o]\alpha, \tag{4}$$

where :

α = average land area needed to park a vehicle .

As a proportion of the total area within the circle, parking requires:

$$P_p(r) = \frac{N\alpha}{oar^2} \quad . \tag{5}$$

To gauge the relative magnitude of parking and highway space in the vicinity of a work center, the point where the freeway and parking proportions are equal, r, can be calculated as below. (Bear in mind that the highway percentage does not count through trips, and the parking percentage does not include non- peak trips)

$$P_h(\tilde{r}) = P_p(\tilde{r}) \tag{6a}$$

$$\frac{Ndw(\ell)}{ot_p v\pi\tilde{r}} = \frac{N\alpha}{oa\tilde{r}^2} \quad . \tag{6b}$$

Eq. 6 can be rewritten as:

$$r = \frac{\alpha v t_p}{d w(\ell)} . \qquad (7)$$

For example, a comparison between urban highways (25.5'/lane) and 5-level parking garages (70 feet per space), with t_p = 2 hours and v/d = 2000 vehicles/hour, yields r = 2.1 miles. This translates into a work center of nearly 14 square- miles, a truly enormous size. Table 6 provides results for different highway and parking types (parking parameters are derived from Chrest et al, 1989). Although parking area can be reduced through use of multi- story garages, construction cost and accessibility to upper floors pose practical limits on garage height. Hence, there is considerable reason to question the wisdom of increasing the capacity of highways entering an urban core when there may not be sufficient space to absorb the vehicles once they arrive.

F. Discussion

Overall, the potential gains in space efficiency are limited for three reasons : (1) A large proportion of highway width is devoted to buffer and shoulders, which may not be affected by automation; (2) In congested city centers , demand for parking space can overwhelm the space needs of highways; (3) Automation may not be capable of reducing interchange size.

These facts aside, automation can still be effective at adding capacity in places where available space is greatly restricted. For instance:

Table 6. Space Occupied by Highways and Parking in a Work Center

PERCENTAGE OF AVAILABLE SPACE (100,000 Employees)

Radius of Work Center (mi)	Highway Type			Parking Type		
	Rural	**Urban**	Crush	1-level	Attended	5-level
.25	18.1	12.3	5.8	438.4	175.4	102.3
.50	9.0					25.6
1.00	4.5	6.1 3.1	2.9 1.4	109.6 27.4	43.8 11.0	6.4
1.50	3:o	2.0	1.7	16.9	4.9	2.8
2.00	2.3	1.5	.6	4.4	2.7	1.6
2.50	1.8	1.2			1.8	1.0
3.00	1.5	1.0	.5	3:o	1.2	.7

PERCENTAGE OF AVAILABLE SPACE (1,000,000 Employees)

Radius of Work Center (mi)	Highway Type			Parking Type		
	Rural	**Urban**	Crush	1-level	Attended	5-level
.25	181	123	58	4384	1754	1023
.50	90	31	29	1096	438	256
1.00	45	20	14	274	110	64
1.50	30		10	121	49	28
2.00			7	69	27	16
2.50	23 18	15 12	6	44	18	10
3.00	15	10	5	30	12	7

Highway Sizes: 37.5 feet per lane for rural (300' right-of-way for 8 lanes)
25.5 feet per lane for urban (204' right-of- way for 8 lanes)
12 feet for crush (96′ for 8 lanes)

Parking Sizes: 300 square- feet/car for 1- level
120 square-feet/car for attendant (1-level without aisles)
70 square- feet/car for 5- level

Assumes: t_p = 2 hours, v/d = 2000 vehicles/hour, o = 1.25

(1) Expansion of congested urban highways that are constrained by surrounding land uses, especially when a large proportion of traffic has destinations outside the city center.

(2) Hills where extensive grading is required, or tunnels or bridges.

Automation can produce benefits that go beyond travel time reduction: it can make the journey more relaxing and comfortable. Nevertheless, the most immediate application of automation seems to be in bridging bottlenecks, the focus of the next section of the paper.

CHAPTER 6 REDUCING DELAY IN A BOTTLENECK

As discussed in the previous chapter, automation may initially be used to relieve congestion at highway bottlenecks. Therefore, to select potential sites, there will be a need to assess the time benefits of new technologies at isolated bottlenecks (as opposed to the network-wide impacts; Gardes and May, 1990; Sullivan and Wong, 1989). This chapter gives a preliminary indication of how technology can affect travel time through a bottleneck. A follow-up report will examine this issue in greater depth, through use of the simulation program “Bottleneck Traffic Simulator . "

A. Average Time

The time required to traverse a highway bottleneck can be viewed as the sum of three values:

$$T = t_c(c) + t_t + t_r , \qquad (8)$$

where :

$t_c(c)$ = congestion delay at the entrance to the guideway, with capacity c

t_t = transfer delay accessing the guideway

t_r = time en route traversing the guideway.

Ordinarily, the access time does not exist. But in the case of automation, access time may be needed for the transition from manual control to automatic control.

The congestion delay depends on the bottleneck capacity, which can be measured as m(v/d), where m is the number of lanes. The en route time depends on velocity as well, so the total time can be expressed as:

$$T = t_c(mv/d) + [t_t + (\ell/v)], \tag{9}$$

where :

ℓ = length of the bottleneck

m = number of lanes.

Because capacity depends on both v and d, it is possible to reduce total travel time without increasing velocity. Hence an analysis was performed to compare the benefits of increasing capacity to the benefits of reducing transfer/en route time. Congestion delay was estimated from a cumulative arrival curve recorded during the a.m. peak of June 12, 1990, on Highway I- 5 northbound in the vicinity of Burbank, California (Figure 7). This road segment was selected because it tends to be uncongested in the morning, both upstream and downstream, and counts are reflective of true arrival times (not departure times). For the case where k = 2, traffic flows have been modified as follows:

$$f_i = \bar{f} + k(f_i-\bar{f}) , \tag{10}$$

where :

f_i = traffic flow recorded in time slice i

$\bar{f}$ = average traffic flow over 6:00-9:00 a.m. period.

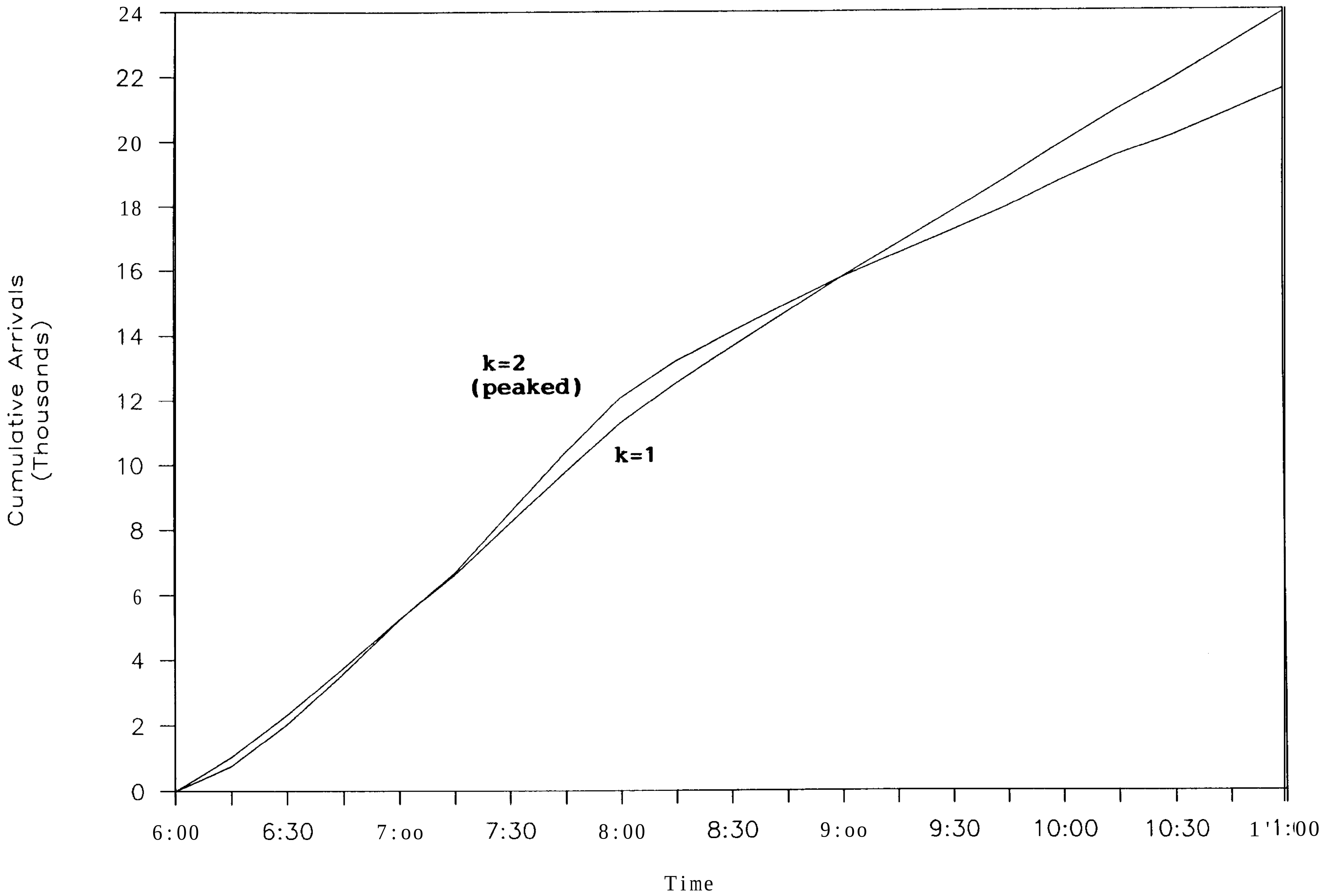

Figure 7. Cumulative vehicle count recorded June 12, 1990, on Highway I-5 northbound in Burbank, California (k=1 case). Peaked curve (k=2) is modified from Burbank data.

Hence, the traffic peak is accentuated, but the 3-hour average is held constant, leading to more queueing.

Figures 8 and 9 illustrate how total travel time over the 6:00 - 11:00 a.m. period depends on the combined factors of transfer/en route time $[t_t + \ell/v]$ and capacity. Capacity has been expressed as a percentage, relative to the average arrival rate during the 6:00 to 9:00 period. The figure shows how capacity gains can be traded against travel time improvements. Capacity gains are most important when capacity is below the 110% level, when congestion is most significant. When capacity is large, improvements in the transfer/en route time provide the greatest gains.

An important qualification is that reductions in transfer/en route time accrue throughout the day, whereas capacity benefits only accrue during the peak periods. Hence, the figures somewhat overestimate the benefit of increasing capacity.

B. Route Selection

A bottleneck might be served by both automated and manual lanes. Because these lanes can differ with respect to access time, capacity and velocity, the different lanes may experience different levels of congestion.

Suppose that the system is defined by the following parameters:

$A(t)$ = cumulative arrival of vehicles, up to time t
c_i = total capacity among lanes type i
t_i = sum of access and en route time, for lanes type i .

For the purpose of illustration, suppose that all vehicles are equipped for automation and that travelers choose the lane type that offers the minimum

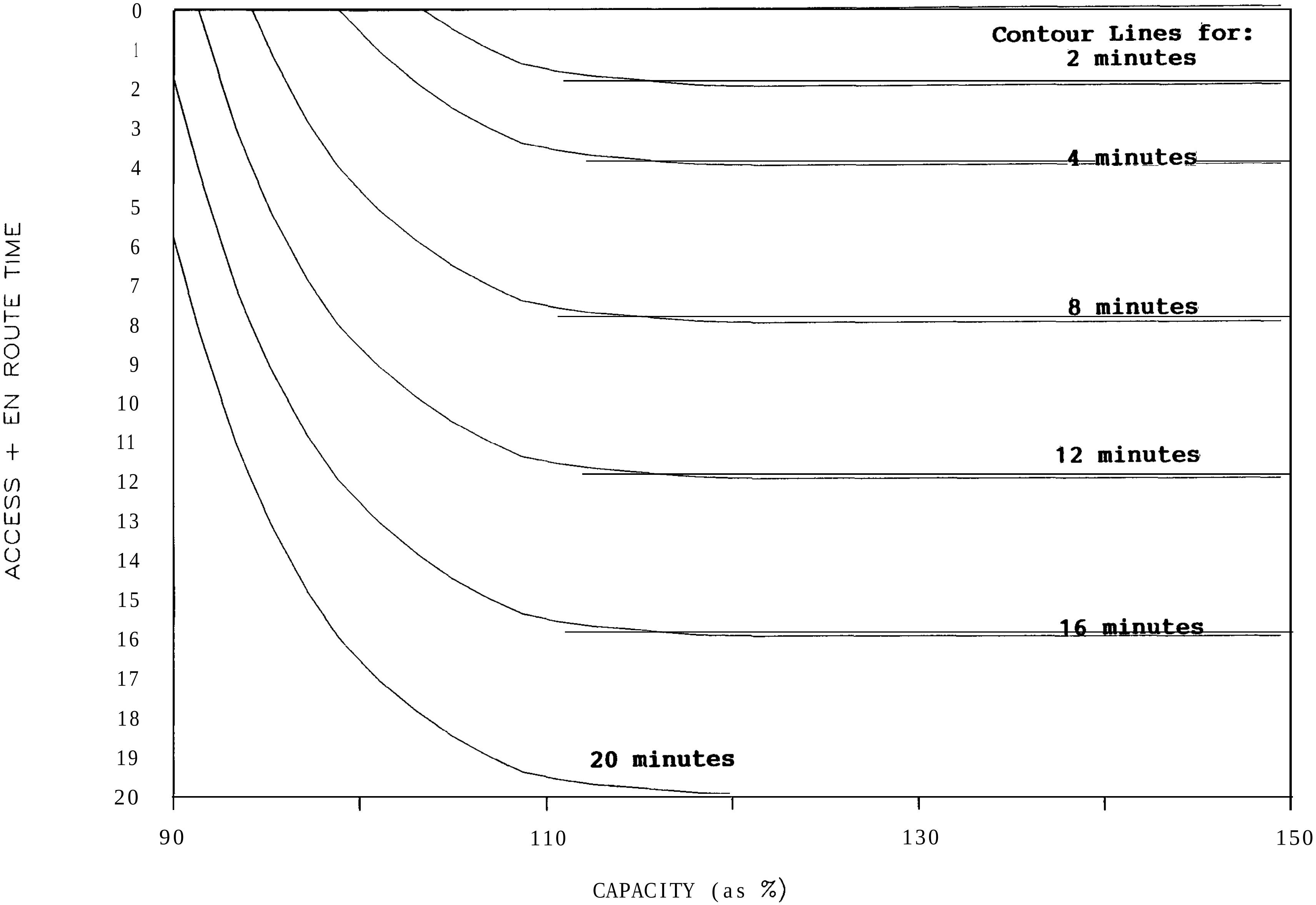

Figure 8. Contour lines for total travel time. Congestion delay derived from arrival curve in Figure 7 (k=1 case). Capacity is percentage relative to average arrival rate between 6:00 a.m. and 9:00 a.m.

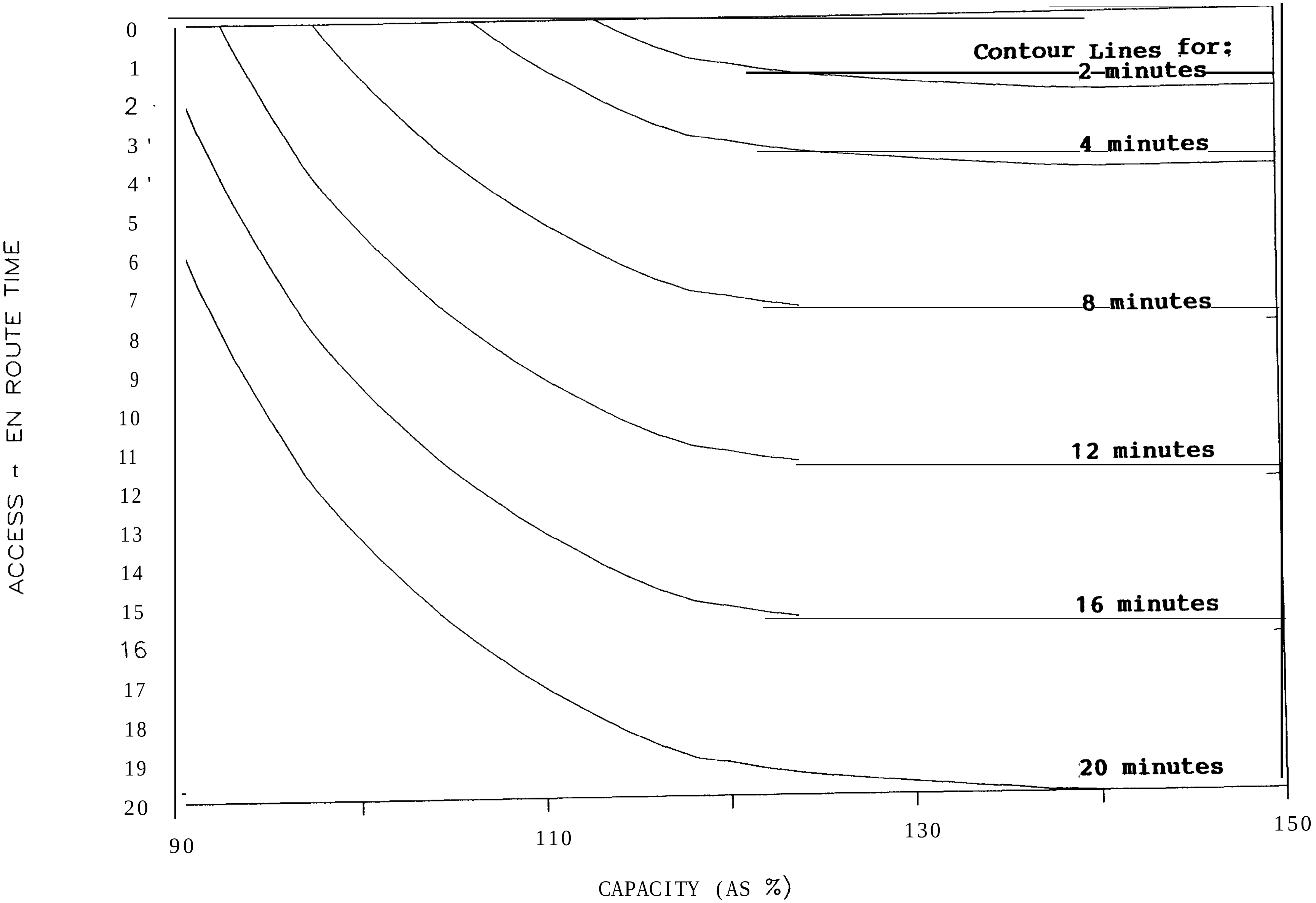

Figure 9. Contour lines for total travel time. Congestion delay derived from arrival curve in Figure 7 (k=2 case). Capacity is percentage relative to average arrival rate between 6:00 a.m. and 9:00 a.m.

total travel time. Then, in equilibrium, the total travel time among the lane types used must be equal.

Figure 10 demonstrates the formation of an equilibrium for a hypothetical cumulative arrival curve. In this example, the following parameters are used:

t_1 = 0 minutes t_2 = 10 minutes c_1 = 8,000 veh/hr c_2 = 14,000 veh/hr

The relative en route times are somewhat exaggerated for the purpose of illustration.

Phase 1 Initially, the capacity of Route 1 exceeds the arrival rate. All vehicles choose Route 1 and no queue develops.

Phase 2 The arrival rate exceeds the capacity of Route 1. Queues begin to form, but still no vehicles use Route 2 because the added travel time exceeds the queue time.

Phase 3 The queue time equals t_2-t_1, so vehicles begin to use Route 2. Time in queue stays constant at t_2-t_1 for Route 1, with no queueing at Route 2.

Phase 4 The arrival rate exceeds the capacity of Routes 1 and 2 combined, Queues form for both Route 1 and Route 2. However, the difference in queue time remains constant at t_2-t_1 .

Phase 5 The queue at Route 2 has vanished. The time in queue at Route 1 returns to t_2-t_1 .

Phase 6 The arrival rate has fallen below the capacity of Route 1. The queue at Route 1 begins to decline and no vehicles use Route 2.

Phase 7 The queue at Route 1 has vanished.

Figure 11 shows the vehicle departure rates associated with the cumulative arrival curve in Figure 10. Note that Route 2 is used intensively, but only over a short period of time -- about an hour-and-a-half, during Phases 3-5.

If future highway automation requires a significant access time, then it may be that travelers will only choose to use the automated route during a relatively short part of the day. The benefits of automation would accrue to

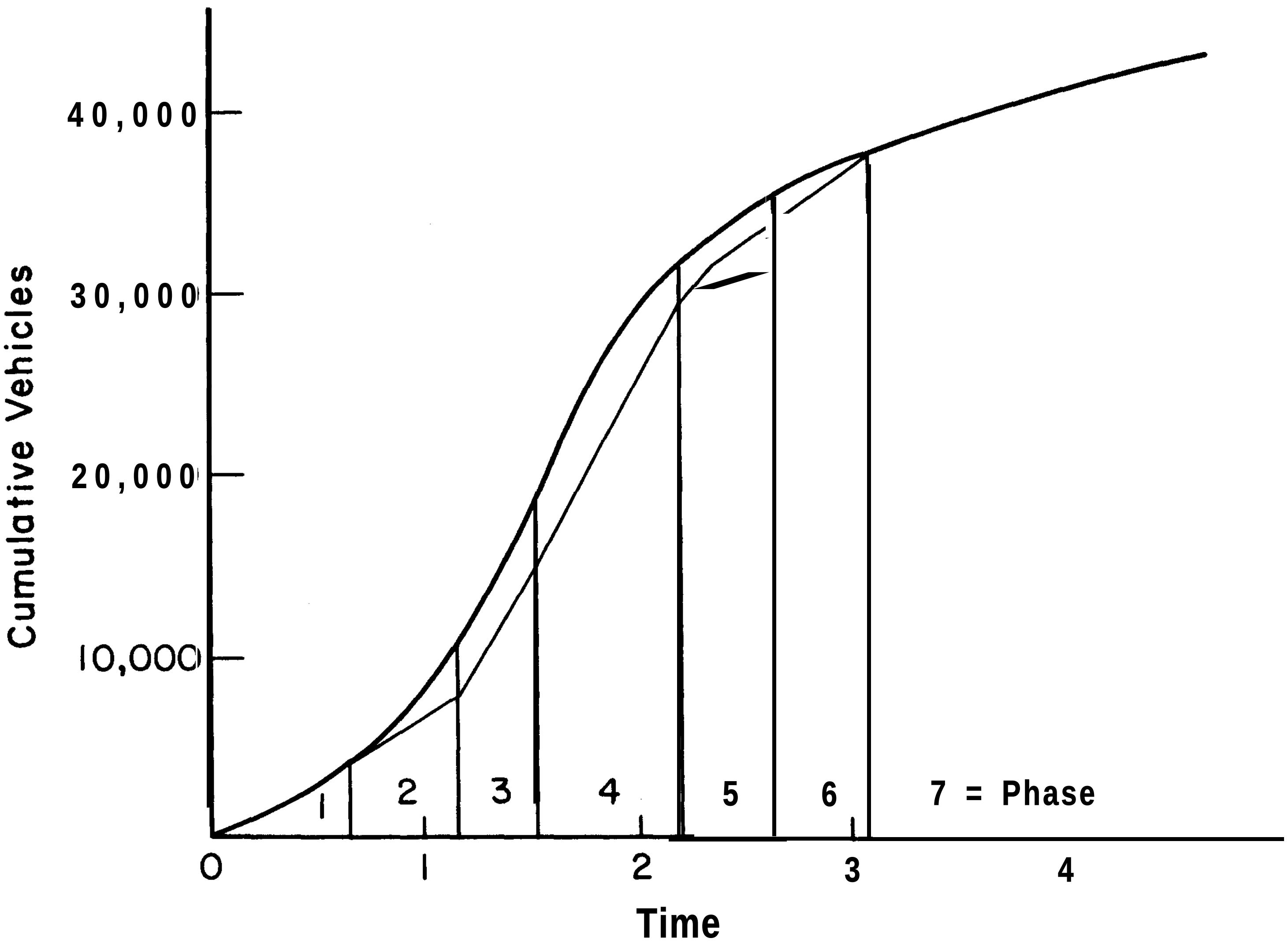

Figure 10. Cumulative arrival and departure of vehicles at a highway bottleneck. Vehicles use Route 2 only during Phases 3-5.

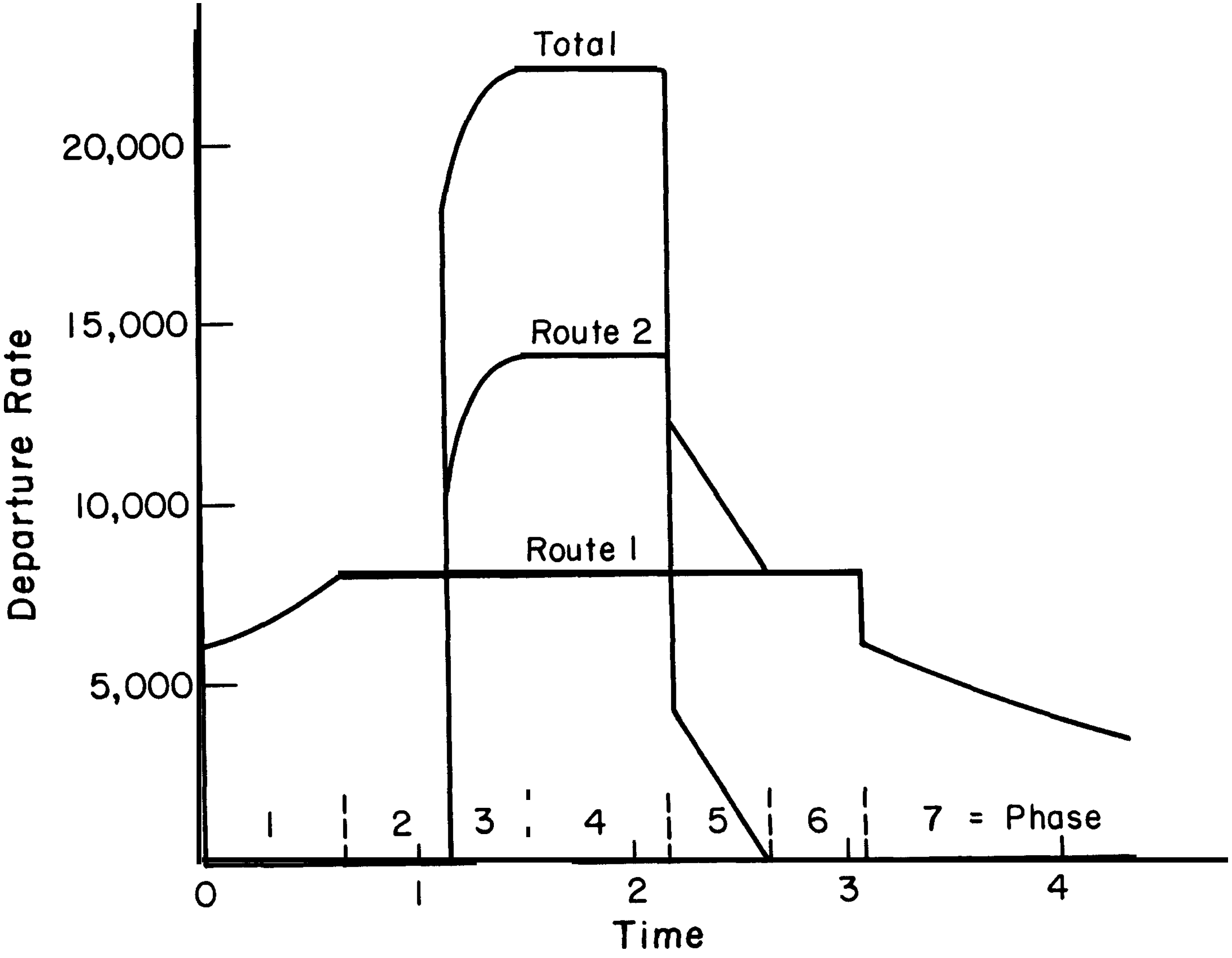

Figure 11. Departure rates corresponding to Figure 10.

the drivers traveling during the peak commute periods. Outside of these peak hours, there conceivably may be a time benefit if the automation is turned off, allowing vehicles to traverse the highway in ordinary manual mode.

CHAPTER 7 CONCLUSIONS

Even simple forms of highway automation can provide important travel time benefits. Automated low- speed and stationary merging can reduce queueing at the entrances to bridges, tunnels and other bottlenecks. "Mini- highways" can reduce delays crossing urbanized areas. And "high- speed highways" can make long-distance travel faster and more enjoyable. None of these three ideas requires a capability to merge traffic streams at high speed. High- speed merging, which appears to be the most distant technology, would be most useful in urbanized corridors with significant on- and- off movements. But even here, automated express lanes might be effective.

Any move toward automation must be viewed against the background of its alternatives . If space-efficiency is the goal, then gains in parking efficiency, local street efficiency and highway efficiency should all be compared. For instance, car-pooling and mass transit reduce both guideway and parking requirements, whereas highway automation does not. Still another possibility is roadway pricing.

Highway automation will likely achieve great benefits within a few niche markets. These markets may be in congested existing cities, rather than radically transformed "cities of the future." Automation can help existing cities cope with automobile traffic within the limited space available.

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